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Assessment of heavy metal pollution in seawater, benthic flora and fauna and their ability to survive under stressors along the northern Red Sea, Egypt

by

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Abstract

The purpose of this study was to assess the north coasts of the Egyptian Red Sea, including Ras Gharieb, Hurghada, Safaga and Qusier, by evaluating the heavy metal pollution in seawater and benthic flora and fauna in the winter and summer of 2016. The concentrations of heavy metals (Fe, Mn, Zn, Cu, Ni, Cd and Pb) were analysed with an atomic absorption spectrophotometer. The results revealed that the Fe levels in the seawater ranged from 7.86 and 27.95 µg l^{-1}, while the Zn concentrations fell between 1.83 and 5.63 µg l^{-1}. In contrast, the recorded values of Mn, Cu, Ni, Pb and Cd in the seawater were minimal at the study sites. Regarding the biota samples, Porifera species were more adaptable than others to an accumulation of most metals in their tissues. Furthermore, seaweeds and seagrasses demonstrated remarkable adaptation in highly polluted regions, especially those with high turbidity, landfilling, sedimentation and high eutrophication rates – much more than the benthic fauna. Our research highlights the critical need for strict regulation of metal emissions in these coastal regions.

Key words: Red Sea, heavy metals, seawater pollution, bioaccumulation, marine fauna, flora

1. Introduction

Heavy metals are among the most serious pollutants in the environment, and they have attracted widespread concern around the world due to their inherent toxicity, persistence and bioaccumulation in the food chain as well as their negative effects on the environment and human health (Bosch et al. 2016). Heavy metals in the coastal environment occur naturally due to weathering processes and appear as a result of anthropogenic activities such as mining, shipping, tourism and the combustion of motor fuels (Nour & El-Sorogy 2020; Salah-Tantawy et al. 2022a). Because of the low baselines of metals in seawater and the influence of seawater matrix effects, measuring dissolved metals in seawater is much more difficult than measuring metals in sediments. Thus, only a few field studies have been conducted on the distribution and risk of metals in seawater (Li et al. 2017; Li et al. 2019; Liu et al. 2021).

Many marine organisms can regulate heavy metals within their tissues. Some heavy metals are essential for different metabolic processes, but are highly toxic for aquatic organisms and those who consume them when the recommended safety levels are exceeded (Rajeshkumar & Li 2018). The ability of invertebrates to adsorb heavy metals is largely dependent on the physical and chemical characteristics of the metal and the seawater in which they live. Marine organisms such as clams, bivalves, cockles (Maanan 2008; Soegianto et al. 2020) and gastropods (Hamed & Emara 2006) have been used as bio-indicators for heavy metal pollution (Neuberger-Cywiak et al. 2003). Mollusca has assumed a major role in the monitoring of contaminants worldwide (Belal et al. 2016; Dar et al. 2018). In addition, bivalves are filter-feeders and thus uptake heavy elements not only from food and water, but also from ingesting inorganic particulate matter (El-Sikaily et al. 2004). Furthermore, coral reefs around the world are subject to extensive anthropogenic damage, including heavy metal pollution (Abdel-Aziz & Dar 2010; Dar 2004). Heavy metals may directly replace calcium within the aragonite skeletal framework, as suspended particulate matter introduced into the skeletal pore spaces (Dar 2004) or as metals incorporated within the carbonate skeleton during biosynthesis (Ali et al. 2011; Fairbanks et al. 1997; Sun et al. 2020). Putten et al. (2000) documented that the metals are incorporated into the skeletal organic matrix or trapped as separate mineral phases (Putten et al. 2000). Regardless of the incorporation mechanism, corals are good tracers of pollutants in the marine environment (Ali et al. 2011).

Likewise, seagrasses and seaweeds (macro-algae) are used as bio-monitors for changes in heavy metal content and availability in the marine environment (Khaled et al. 2014; Parus & Karbowska 2020; Ryan et al. 2012). Macro-algae are widely distributed in the aquatic environment; they are sedentary and easy to collect and identify (Campanella et al. 2001; Conti 2002). Macro-algae can accumulate levels of heavy metals reaching thousands of times higher than the corresponding concentrations in seawater (Conti & Cecchetti 2003). Seagrasses are a unique group of flowering plants that are adapted to exist fully submerged in the sea, and they profoundly influence the physical, chemical and biological environment of coastal waters (Wright & Jones 2006). Seagrasses are major contributors to primary productivity (Klumpp & Van der Valk 1984), taking up heavy metals from seawater through their leaf surfaces and from sediment and interstitial waters through their roots (Caccia et al. 2003; Ferrat et al. 2003). They are thus considered the most important heavy metal reservoirs (Amado Filho et al. 2004; Thangaradjou et al. 2010).

The essential aim of the research was to conduct a comprehensive study of seven heavy metal concentrations (Fe, Zn, Cu, Mn, Ni, Pb and Cd) in the coastal environment of the northern Red Sea cities of Ras Gharieb, Hurghada, Safaga and Qusier using seawater and benthic flora and fauna to determine the extent of human impact on the coastal environment, to assess the ability of available biota to survive under different stressors and to compare the degree of pollution and distribution of heavy metals in the study area against previous global studies.

2. Materials and methods

2.1. Study areas

The study areas extended for about 290 km along the Red Sea coastline, from Ras Gharieb (150 km northern of Hurghada) to Qusier (140 km south of Hurghada). The selected study stations were located in tidal flat zones off the main cities of Ras Gharieb (n = 8), Hurghada (n = 11), Safaga (n = 10) and Qusier (n = 10) (Fig. 1). These cities are exposed to over-population and severe land-based activities involving oil exploration and production, maritime activities, tourist activities, marine wharves, marinas, shipyards, desalination plants, sewage treatment stations, fishing operations and harbours, land reclamation, mining and shipping operations, subsurface untreated sewage runoff and human waste dumping in the tidal flats, as well as temporary flash floods and non-point sources.

Figure 1

Map of sampling stations along the northern Red Sea, Egypt. (A) Northern Red Sea, (B) Ras Gharieb, (C) Hurghada, (D) Safaga, and (E) Qusier (source: Google Earth program).

2.2. Determination of heavy metals in seawater

Thirty-nine seawater samples were collected semi-annually from the study stations with a water sampler (PVC tube with a capacity of approx. 3 liters) into acid-washed polyethylene bottles, then transported immediately in an ice box to the laboratory, where the pH of the samples was adjusted to 3–4 (Brown & Holley 1982). The seawater samples were filtered as soon as possible after collection through a 0.45-µm membrane to remove any suspended materials; their pH value was checked.

Heavy metals in the filtered seawater were pre-concentrated by complexing the metals with ammonium pyrrolidine dithiocarbamate (APDC); the complex compound was extracted into methyl isobutyl ketone and back-extracted into an acidic aqueous solution (Brewer et al. 1969). Five ml of the APDC suspension was added to 1 liter of the seawater sample, which was continuously shaken until chelation was complete (~5 min). A volume of 35 ml of methyl isobutyl ketone was then added and the solution mixed by magnetic stirrer for 5 min for complete extraction. The resulting organic complex layer was drawn by a separating funnel, evaporated until dry, dissolved into 2 ml of HNO_3, filtered and completed to 10 ml with double distilled water (DDW) prior to analysis (Boniforti et al. 1984). The concentrations of heavy metals were measured using a flame atomic absorption spectrophotometer (FAAS, GBC-932) at the National Institute of Oceanography and Fisheries in Egypt. The resulting data are expressed in $\mu g\ l^{-1}$.

2.3. Assessment of the heavy metal concentrations in benthic fauna

The available benthic fauna was collected from each city by scuba diving and snorkelling. A total of 70 specimens representing 28 genera and 40 species of benthic fauna were collected semi-annually from the study stations (Supplementary Table 1). After the sampling process, all specimens were kept in polyethylene bags and transferred to the laboratory in an ice box. The collected specimens of marine fauna were identified according to Macfadyen (1936), Sung et al. (2009), Veron (2014) and Verseveldt (1982).

The benthic fauna samples were washed with fresh water several times to remove any adhering materials and then dried in direct sunlight. Approximately 10 g of each specimen was powdered using an automatic agate mortar. To measure the bio-available heavy metals (Fe, Mn, Zn, Cu, Ni, Pb and Cd), 0.5 g of each powdered sample was digested according to Chester et al. (1994) in nitric acid (HNO_3) and perchloric acid ($HClO_4$) (3:1) until completely dissociated. The samples were then digested on a hot plate. The residue of each sample was dissolved into 2 ml of 12N HNO_3, diluted to 25 ml with DDW, then filtered using a filter paper (Whatman, USA). The heavy metal concentrations were measured using an FAAS (GBC-932) at the National Institute of Oceanography and Fisheries, Egypt. The results are expressed as $\mu g\ g^{-1}$.

2.4. Assessment of the heavy metal concentrations in benthic flora

The study stations were surveyed and the available macro-algae and seagrasses were collected at each city by scuba diving and snorkelling. A total of 34 specimens representing 15 genera and 16 species were collected semi-annually from the study sites (Supplementary Table 2). After collection they were kept in polyethylene bags and transferred immediately to the laboratory in an ice box. The collected specimens of marine benthic flora were classified or identified according to El Shaffai (2016) and Jha et al. (2009).

The collected flora samples were washed several times with fresh water to remove any foreign adhering materials. The samples were air-dried and then powdered using an automatic homogeniser to assure complete homogeneity. To determine the bio-available Fe, Mn, Zn, Cu, Ni, Pb and Cd, 0.5 g of each powdered sample was digested using a 10-ml mixture of HNO_3 and $HClO_4$ (3:1) until complete (Chester et al. 1994). They were then evaporated and the residue was dissolved with 2 ml of 6N HNO_3, then diluted to 25 ml with DDW and filtered using a filter paper. The concentrations of bio-available heavy metals were determined using an FAAS, and the results are expressed as $\mu g\ g^{-1}$.

2.5. Statistical analysis

The data were statistically analysed in the software programme R version 4.1.3. The heavy metal concentrations in seawater were plotted in R script using the '*geom_bar*' function in the '*ggplot2*' package, version 3.3.6. All findings are expressed in tables and visualised in figures as means ± SD.

3. Results and Discussion

3.1 Heavy metal concentrations in seawater

Heavy metal contamination in the marine environment represents a major worldwide environmental threat (Salah-Tantawy et al. 2022a). Its abundance implies dramatic changes in environmental conditions and provides the basis for identifying anthropogenic influences on marine environments (Al-Rousan et al. 2007; Fallon et al. 2002; Jayaraju et al. 2009). Heavy metal content in seawater is highly dependent upon some physicochemical characteristics: pH, salinity, suspended particulate matter and organic matter content (Hatje et al. 2003; Salah-Tantawy et al. 2022b).

3.1.1.Iron (Fe)

Iron is the fourth most abundant element in the earth's crust; it may be present in natural waters in varying quantities, depending on the geology of the area and other chemical components of the waterway. It has a terrestrial origin mainly derived from igneous, metamorphic and sedimentary rocks during erosion, weathering and chemical operations. Serving more biological roles than any other metal, it occurs in two main oxidation forms: an oxidising state ($Fe^{\pm 3}$), which forms insoluble compounds, and a ferrous state ($Fe^{\pm 2}$), which is soluble in aqueous media (USEPA 1986).

In this study, the average values of Fe in the seawater ranged between 7.86 and 27.95 µg l^{-1}, which is much higher than measurements from most seas (0.06–0.17 µg l^{-1}), including the Arabian Sea (Ferrier-Pagès et al. 2001; Measures & Vink 1999). The highest average values of Fe were recorded at Qusier and Ras Gharieb (Fig. 2A) in summer, due to increased terrestrial runoff from coastal activities and subsurface

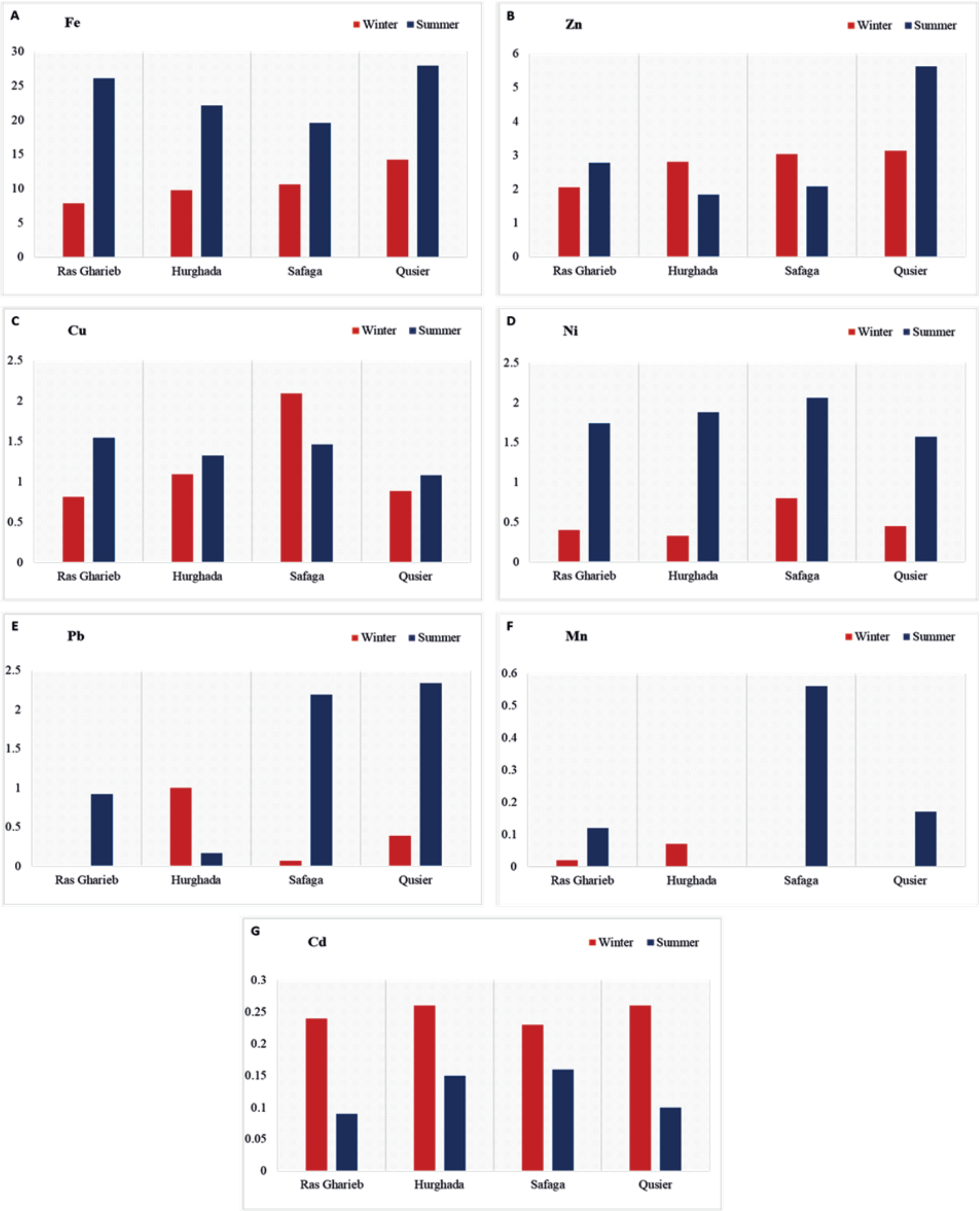

Figure 2

The averages of heavy metals concentration in seawater (µg l^{-1}) at the studied areas along the northern Red Sea during winter and summer wastewater seepage. Whereas the Fe values were greater than those Al-Wesabi et al. (2015); Shriadah et al. (2004), while it consistent with Ali et al. (2011), Bazzi (2014), and El-Metwally (2015) (Supplementary Table 4).

3.1.2. Zinc (Zn)

Zinc is an essential heavy element for most organisms in their growth and development. It can enter the environment from both natural and anthropogenic activities (Valiela & Whitfield 1989). Figure 2B illustrates the concentrations of Zn at the study sites. In our study, the averages of Zn concentrations in seawater were within the normal range for the world's open oceans (~5 μg l^{-1}) as reported by Riley and Chester (1971) and the Australian Water Quality for 99% protection of marine species (~7 μg l^{-1}) reported by ANZECC (1994) and ARMCANZ (2000) (Supplementary Table 3). The recorded Zn values at the study sites were higher than those reported by Al-Wesabi et al. (2015), El-Metwally (2015) and Shriadah et al. (2004), but lower than those in the studies of Abouhend and El-Moselhy (2015), Ali et al. (2011), Dar et al. (2016) and Madkour and Dar (2007) in different regions of the Red Sea. Meanwhile, our results were similar to those recorded by Abd El-Wahab et al. (2005) (Supplementary Table 4).

3.1.3. Copper (Cu), Nickel (Ni), Lead (Pb), Manganese (Mn) and Cadmium (Cd)

The values recorded at the different tidal flats of the selected cities for concentrations of Cu, Ni, Pb, Mn and Cd were minimal, as shown in Figs. 2C–G.

3.2. Bioaccumulation of metals in marine fauna and their ability to survive under stressors

The benthic fauna collected in this study showed varying abilities to accumulate heavy metal within their structures. Table 1 illustrates the concentrations of heavy metals in the collected fauna at Ras Gharieb. The lowest values of faunal diversity were recorded at Ras Gharieb: The benthic fauna was represented by six species, including soft corals, hard corals, echinoids and gastropods (Supplementary Table 1). *Heteroxenia fuscescens* (soft coral) demonstrated a great ability to accumulate significant amounts of Zn (446.59 μg g^{-1}), while *Echinometra mathaei* recorded significant Pb (65.55 μg g^{-1}) and Cd (5.50 μg g^{-1}) levels. Another species of soft coral, *Sarcophyton trocheliophorum*, accumulated 8.45 μg g^{-1} of Ni. According to these estimated values, the accumulation sequence was in the following order: soft corals > echinoids > hard corals > Mollusca. The tidal zone of Ras Gharieb is highly impacted by dense petroleum pollution, which affects the faunal diversity and distribution. Consequently, the recorded species have a great deal of adaptability to survive under these severe amounts of pollution.

Additionally, the tidal flat of Hurghada suffers from different types of pollution from land-based activities that affect the benthic faunal types, distribution and diversity. Under these severe conditions, 22 species of adaptable, surviving organisms were collected – Porifera, soft coral, hard coral, Mollusca and echinoids (Supplementary Table 1). These species have varying abilities to accumulate heavy metals. As illustrated in Table 2, sponge species (*Plakinastrella onkodes* and

Table 1

Average values of heavy metal concentrations in marine fauna (μg g^{-1} dry wt.) at Ras Gharieb during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Acropora austere*	112.50 ± 5.12	12.13 ± 1.23	9.50 ± 0.06	BDL	2.75 ± 0.07	BDL	BDL
	Stylophora pistillata	160.10 ± 3.71	6.10 ± 1.18	9.60 ± 0.21	0.80 ± 0.4	2.95 ± 0.06	BDL	BDL
	Sarcophyton trocheliophorum	74.85 ± 10.19	4.91 ± 0.08	77.85 ± 0.16	4.12 ± 1.01	6.74 ± 1.22	7.02 ± 5.10	3.02 ± 0.09
	Strombus triangulates	61.20 ± 2.99	5.35 ± 0.04	17.00 ± 0.02	BDL	2.90 ± 0.03	BDL	BDL
	Echinometra mathaei	115.90 ± 9.44	10.65 ± 2.14	17.55 ± 0.41	2.40 ± 0.02	1.70 ± 1.03	65.55 ± 3.91	5.50 ± 1.33
Summer	*Acropora austere*	85.48 ± 13.15	4.75 ± 0.06	12.98 ± 0.11	BDL	5.98 ± 1.24	20.15 ± 0.91	1.03 ± 0.27
	Stylophora pistillata	180.10 ± 22.40	9.70 ± 0.56	17.40 ± 0.52	BDL	5.20 ± 2.19	BDL	0.90 ± 0.03
	Sarcophyton trocheliophorum	86.70 ± 12.03	6.05 ± 1.20	80.45 ± 1.02	2.40 ± 0.92	8.45 ± 3.61	5.45 ± 0.19	1.10 ± 0.73
	Heteroxenia fuscescens	240.50 ± 29.81	14.50 ± 1.18	446.59 ± 61.45	0.65 ± 0.10	4.45 ± 0.28	BDL	3.05 ± 0.06
	Echinometra mathaei	165.35 ± 31.15	6.30 ± 2.40	29.95 ± 0.06	BDL	1.55 ± 0.08	8.90 ± 1.22	1.55 ± 0.03

* BDL: below detection limit

Hyrtios protius) have a strong tendency to incorporate very high amounts of Fe (2011.31 and 852.10 µg/g, respectively) within their structures, followed by the echinoid species *Clypeaster audouini* (531.40 µg/g) and the Mollusca species *Tridacna maxima* (294.85 µg/g). Furthermore, *Plakinastrella onkodes* accumulated high Mn (75.75 µg/g) and Cu (22.95 µg/g) levels relative to the other benthic fauna, and the soft coral *Dendronephthia hemprichi* was found to have very high Zn content (196.95 µg/g) compared with the other species. *Tectus dentatus* showed high Pb accumulation, though it recorded an insignificant amount of Cd. Generally, the heavy metal content in the benthic fauna at Hurghada followed the descending bioaccumulation ability order: Porifera > soft corals > echinoids > Mollusca > hard corals.

Long ago, Safaga Fishing Harbour was used to finish and repair fishing boats. Moreover, it receives huge amounts of fine-particle sediments and heavy metals from trading and phosphate harbours as well as many other coastal activities. Twelve faunal species had adapted to these poor conditions, representing Porifera, hard corals, soft corals and Mollusca (Supplementary Table 1). *Plakinastrella*

Table 2

Average values of heavy metal concentrations in marine fauna (µg g^{-1} dry wt.) at Hurghada during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Hyrtios protius* (grey sponge)	852.10 ± 117.19	16.30 ± 2.46	19.80 ± 0.13	6.55 ± 0.14	6.30 ± 1.80	BDL	BDL
	Plakinastrella onkodes (black sponge)	1402.95 ± 375.01	75.75 ± 1.97	54.05 ± 0.06	9.85 ± 0.32	12.65 ± 1.09	BDL	0.25 ± 0.08
	Acropora polystoma	162.30 ± 5.27	5.70 ± 1.71	8.65 ± 0.10	6.65 ± 0.09	5.65 ± 2.02	10.70 ± 3.28	2.85 ± 0.01
	Stylophora pistillata	255.90 ± 13.28	0.75 ± 0.04	12.65 ± 0.10	0.85 ± 0.25	3.75 ± 0.51	BDL	0.10 ± 0.01
	Favites complanata	161.95 ± 25.78	4.90 ± 0.57	5.30 ± 0.05	2.45 ± 1.02	10.20 ± 2.14	BDL	0.55 ± 0.09
	Strombus triangulatus	127.05 ± 60.22	4.45 ± 0.48	6.25 ± 0.05	0.60 ± 0.14	3.25 ± 0.99	BDL	BDL
	Tridacna maxima	294.85 ± 35.17	9.05 ± 2.38	14.00 ± 0.07	BDL	1.20 ± 1.01	27.60 ± 1.14	4.70 ± 1.02
	Murex tribulus	220.85 ± 22.70	10.10 ± 1.47	45.70 ± 0.29	10.95 ± 3.12	4.75 ± 0.82	BDL	1.85 ± 0.38
	Tripneaustus gratella	152.25 ± 18.15	8.80 ± 1.26	8.35 ± 0.10	BDL	1.35 ± 0.24	BDL	0.35 ± 0.08
	Clypeaster audouini	531.40 ± 63.28	14.00 ± 0.81	7.45 ± 0.12	1.25 ± 0.06	3.90 ± 0.61	BDL	0.10 ± 0.005
Summer	*Hyrtios protius* (grey sponge)	465.65 ± 60.24	14.50 ± 0.09	25.95 ± 1.25	4.50 ± 0.91	2.30 ± 1.05	BDL	0.40 ± 0.14
	Plakinastrella onkodes (black sponge)	2011.31 ± 420.1	13.75 ± 0.99	60.90 ± 2.41	22.95 ± 2.41	24.75 ± 6.57	51.30 ± 5.19	2.55 ± 0.48
	Stylophora pistillata	85.10 ± 9.46	8.65 ± 0.96	4.40 ± 2.01	BDL	BDL	BDL	0.10 ± 0.02
	Favia maritima	59.85 ± 3.14	13.30 ± 2.49	3.25 ± 0.31	BDL	4.10 ± 1.22	BDL	0.15 ± 0.05
	Acropora polystoma	64.20 ± 3.71	7.90 ± 1.26	5.60 ± 1.95	BDL	BDL	BDL	0.80 ± 0.14
	Tubipora musica	233.45 ± 80.19	24.25 ± 5.91	16.95 ± 0.94	BDL	3.25 ± 0.68	BDL	0.45 ± 0.01
	Platygyra lamellina	74.65 ± 18.72	10.40 ± 6.17	14.90 ± 11.03	0.55 ± 0.01	3.30 ± 0.71	BDL	1.00 ± 0.23
	Porites lobate	60.70 ± 20.16	7.25 ± 0.63	4.00 ± 0.47	BDL	1.85 ± 0.33	BDL	BDL
	Galaxia fasciularis	61.90 ± 18.22	8.90 ± 0.15	18.70 ± 16.44	0.25 ± 0.03	1.10 ± 0.45	BDL	BDL
	Dendronephthia hemprichi	131.55 ± 23.15	10.60 ± 0.06	196.95 ± 11.02	1.30 ± 0.009	1.00 ± 0.08	5.90 ± 1.13	2.20 ± 0.61
	Sinularia polydactyla	89.60 ± 6.28	4.20 ± 0.13	26.35 ± 6.45	16.20 ± 2.55	0.75 ± 0.26	10.35 ± 7.18	1.50 ± 0.81
	Tridacna gigas	129.15 ± 19.44	21.10 ± 7.16	16.05 ± 0.77	0.30 ± 0.005	2.05 ± 0.77	11.60 ± 5.16	1.65 ± 0.03
	Tectus dentatus	127.70 ± 14.17	3.90 ± 0.07	11.80 ± 0.42	1.25 ± 0.07	0.80 ± 0.03	40.85 ± 3.14	1.50 ± 0.51
	Strombus triangulates	97.85 ± 15.33	3.75 ± 0.01	17.40 ± 0.30	BDL	0.70 ± 0.18	8.45 ± 1.25	2.15 ± 0.92
	Echinometra mathaei	59.30 ± 2.61	10.45 ± 0.08	4.80 ± 0.40	BDL	3.95 ± 0.84	BDL	0.05 ± 0.002
	Ophiocoma scolopendrina	180.95 ± 7.84	11.60 ± 2.17	76.65 ± 3.25	3.35 ± 0.71	5.40 ± 1.32	37.10 ± 2.15	6.70 ± 1.23
	Clypeaster audouini	320.05 ± 35.08	5.25 ± 1.24	11.55 ± 1.23	BDL	1.05 ± 0.65	35.70 ± 2.04	1.40 ± 0.09
	Astropecten irregularis	240.95 ± 69.24	5.75 ± 2.34	105.70 ± 2.52	5.50 ± 0.05	25.15 ± 3.12	BDL	1.85 ± 0.05

* BDL: below detection limit

onkodes (Porifera) works as a scavenger of heavy metals from the surrounding environment, and has an outstanding ability to accumulate significant levels of Fe, Mn, Zn, Ni, Pb and Cd (1768.09, 246.30, 323.75, 14.80, 39.40 and 3.60 μg g^{-1}, respectively) (Table 3). In addition, the Mollusca species *Murex tribulus* was a scavenger of Cu (309.16 μg g^{-1}). The other benthic faunal communities recorded varying degrees of heavy metal accumulation. Heavy metal bioaccumulation in the benthic fauna at Safaga followed the descending ability order of Porifera > Mollusca > hard corals > soft corals.

A poor situation was also found in the tidal flat of Qusier, an area which suffers from underground wastewater seepage and high eutrophication, as well as fine sediment inputs from coastal-based activities (El-Metwally et al. 2017). Despite these challenging conditions, 17 benthic faunal species had adapted within this zone, representing Porifera, hard corals, echinoids and Mollusca (Supplementary Table 1). The Porifera species *Plakinastrella onkodes* was also found to be a powerful scavenger of Fe, Cu and Ni (1817.81, 78.60 and 31.95 μg g^{-1}, respectively), and *Crassostrea* sp. (a bivalve) was enriched with Zn (Table 4). Meanwhile, the hard coral species *Acropora clathrata*, *Acropora valida* and *Galaxia fasicularis* were highly enriched with Pb (131.55, 93.15 and 56.90 μg g^{-1}, respectively). Cd enrichment, meanwhile, was found in significantly high levels in the hard coral species *Acropora valida*, *Acropora clathrate* and *Millopora dichtoma* (12.80, 11.40 and 6.45 μg g^{-1}, respectively). Additionally, the echinoid species *Tripneastus gratella* and *Diadema setosum* recorded significantly high Fe levels. The tendency for heavy metal bioaccumulation in the benthic fauna at Qusier was in the following descending order: Porifera > Mollusca > echinoids > hard corals.

Porifera have a strong ability to concentrate metals in their tissues (Berthet et al. 2005; Cebrian et al. 2007; Johnston & Clark 2007), since they have numerous deep pores that can absorb metals in particle form and calcium can be replaced in their spines. The heavy metals found in the benthic faunal communities may have directly replaced calcium within the aragonite skeletal framework, may have been introduced into the skeletal pore spaces as suspended particulate matter (Dar 2004) or as metals incorporated inside the carbonate skeleton during biosynthesis (Ali et al. 2011; Sun et al. 2020). A previous study documented that heavy metals are not necessarily incorporated into the calcite structure, but can also be adsorbed onto the skeletal organic matrix or trapped as separate mineral phases. Additionally, the bioaccumulation processes within the benthic fauna were controlled by certain factors, including the bio-availability of the heavy metals, the surface area exposed to these metals, the degree of protection from the intensive wave action, turbidity limits and the varying abilities of these organisms to incorporate or assimilate heavy metals within their tissues or skeletons (Vander Putten et al. 2000). Another study summarised that the controlling factors for heavy metal bioaccumulation in the skeletal framework of corals were the exposed surface area for metal uptake, turbidity, overlying mucus thickness and the ability of the metals to substitute inside the crystal lattice of the hard corals (Abdel-Aziz & Dar 2010).

The heavy metal levels we measured in the tidal flat zones of the selected cities were higher than those recorded by Abd El-Wahab et al. (2005), Abdel-Aziz & Dar (2010), Dar et al. (2008), Dar & Abd El Wahab (2005), Dar & Mohammed (2009) and Madkour (2013) at different sites around the Red Sea.

Table 3

Average values of heavy metal concentrations in marine fauna (μg g^{-1} dry wt.) at Safaga during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Pocillopora damicornis*	225.95 ± 38.56	10.70 ± 3.16	9.15 ± 0.90	1.25 ± 0.09	5.55 ± 1.63	BDL	BDL
	Favites abdita	119.35 ± 13.49	9.05 ± 2.19	9.15 ± 1.78	4.90 ± 0.51	7.75 ± 2.88	BDL	BDL
	Stylophora pistillata	177.05 ± 10.18	10.90 ± 0.91	6.50 ± 0.80	1.80 ± 0.08	1.00 ± 0.27	BDL	1.15 ± 0.06
	Acropora humilis	143.45 ± 14.75	13.05 ± 6.01	6.40 ± 0.81	0.70 ± 0.03	3.00 ± 1.61	BDL	0.25 ± 0.13
	Acropora pharoaonis	89.50 ± 27.62	15.70 ± 4.13	33.20 ± 1.91	0.75 ± 0.04	2.85 ± 0.80	BDL	0.20 ± 0.04
	Porites solida	77.85 ± 9.57	8.15 ± 0.88	7.15 ± 1.90	0.65 ± 0.11	3.75 ± 0.47	BDL	BDL
Summer	*Plakinastrella onkodes* (black sponge)	1768.09 ± 575.15	246.30 ± 9.16	323.75 ±5 2.33	27.15 ± 4.12	14.80 ± 4.22	39.40 ± 8.31	3.60 ± 0.61
	Stylophora pistillata	218.05 ± 96.41	8.60 ± 0.63	14.05 ± 0.17	BDL	2.55 ± 0.31	5.35 ± 1.33	1.25 ± 0.04
	Ctenactis crassa	134.05 ± 19.18	4.30 ± 0.08	10.55 ± 0.08	0.55 ± 0.02	0.45 ± 0.09	4.95 ± 0.54	1.60 ± 0.07
	Favites abdita	121.20 ± 17.09	5.25 ± 0.51	25.20 ± 0.84	4.40 ± 0.62	5.95 ± 2.11	0.45 ± 0.03	1.00 ± 0.01
	Acropora austere	118.60 ± 13.12	5.65 ± 3.12	21.15 ± 3.12	BDL	1.65 ± 0.59	5.95 ± 0.90	1.60 ± 0.03
	Sinularia polydactyla	189.50 ± 33.11	9.70 ± 4.31	242.75 ± 152.01	BDL	5.35 ± 3.16	0.90 ± 0.34	2.25 ± 0.33
	Tridacna maxima	211.15 ± 57.48	7.50 ± 1.28	11.55 ± 5.70	BDL	0.85 ± 0.07	12.05 ± 2.01	0.75 ± 0.19
	Murex tribulus	317.30 ± 61.90	4.90 ± 0.82	66.65 ± 1.26	309.16 ± 81.2	1.60 ± 0.04	BDL	2.90 ± 0.41

* BDL: below detection limit

Table 4

Average values of heavy metal concentrations in marine fauna (µg g^{-1} dry wt.) at Qusier during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Plakinastrella onkodes* (black sponge)	1817.81 ± 260.48	33.40 ± 4.72	61.45 ± 0.54	78.60 ± 3.48	31.95 ± 4.21	18.65 ± 0.21	3.65 ± 0.05
	Platygyra carnosus	178.10 ± 10.02	9.45 ± 1.55	6.00 ± 0.02	2.05 ± 0.03	4.10 ± 0.18	BDL	BDL
	Favia pallida	157.55 ± 13.19	9.70 ± 1.99	7.90 ± 0.42	3.60 ± 1.23	2.65 ± 0.09	BDL	BDL
	Favites complanata	128.25 ± 9.29	8.80 ± 0.96	7.60 ± 0.35	3.55 ± 0.80	5.10 ± 1.02	BDL	0.35 ± 0.08
	Porites mayeri	255.90 ± 11.45	7.20 ± 0.18	17.85 ± 0.17	1.00 ± 0.02	5.45 ± 0.51	BDL	BDL
	Millopora dichtoma	82.45 ± 6.55	6.40 ± 0.27	39.10 ± 0.51	2.05 ± 0.17	1.20 ± 0.07	29.70 ± 4.06	6.45 ± 0.29
	Acropora valida	99.25 ± 3.47	8.65 ± 2.30	33.25 ± 0.29	1.05 ± 0.33	5.80 ± 2.50	93.15 ± 8.88	12.80 ± 1.36
	Acropora clathrata	160.90 ± 18.42	7.40 ± 1.36	26.30 ± 0.60	0.05 ± 0.001	3.15 ± 0.42	131.55 ± 11.02	11.40 ± 0.94
	Ctenactis crassa	205.70 ± 29.71	12.55 ± 4.21	6.75 ± 0.88	1.45 ± 0.78	6.65 ± 0.96	BDL	BDL
	Pocillopora damicornis	181.00 ± 18.40	8.50 ± 0.18	7.55 ± 1.15	1.90 ± 0.41	BDL	BDL	BDL
	Stylophora pistillata	144.10 ± 22.49	6.75 ± 0.19	40.70 ± 1.05	0.75 ± 0.15	0.55 ± 0.18	22.35 ± 1.55	3.40 ± 0.07
	Crassostrea sp.	98.70 ± 13.09	9.35 ± 2.15	101.05 ± 2.02	9.35 ± 3.12	4.85 ± 1.223	BDL	BDL
	Diadema setosum	993.00 ± 127.66	22.30 ± 3.25	18.55 ± 0.56	3.65 ± 0.64	5.40 ± 0.86	BDL	0.80 ± 0.03
Summer	*Pocillopora verrucosa*	199.15 ± 16.23	5.45 ± 0.61	18.50 ± 2.31	BDL	4.60 ± 0.51	BDL	2.00 ± 0.91
	Acropora hemprichii	144.50 ± 22.03	0.85 ± 0.13	29.95 ± 0.92	BDL	1.50 ± 0.06	20.50 ± 3.12	2.35 ± 0.05
	Millopora dichtoma	82.25 ± 7.42	3.15 ± 0.17	21.90 ± 0.34	BDL	1.35 ± 0.69	20.30 ± 3.75	0.35 ± 0.93
	Galaxia fascicularis	171.10 ± 11.26	5.35 ± 0.24	36.30 ± 14.02	BDL	3.35 ± 1.48	56.90 ± 6.15	2.45 ± 0.98
	Tripneastus gratella	1700.86 ± 210.10	34.45 ± 3.42	29.90 ± 20.10	1.50 ± 0.08	3.45 ± 0.64	8.30 ± 1.02	1.45 ± 0.08

* BDL: below detection limit

3.3. Bioaccumulation of metals in marine flora and their ability to survive under stressors

Five seaweeds (*Padina boryana*, *Digenea simplex*, *Sargassum cinereum*, *Coralline berteroi* and *Galaxaura marginata*) and one seagrass species (*Halodule pinifolia*) were recorded at Ras Gharieb (Supplementary Table 2). *P. boryana* (a seaweed) is one of the more predominant species throughout the year. Significant concentrations of Fe, Mn, Zn, Cu and Ni were recorded in this species (2673.90, 188.35, 68.45, 28.70 and 50.75 µg g^{-1}, respectively). *D. simplex* had the highest accumulation of Pb (15.05 µg g^{-1}), while *S. cinereum* had the highest Cd concentration (2.20 µg g^{-1}) (Table 5). The recorded heavy metal values in the seagrass species *H. pinifolia* were significantly lower than all the seaweed species.

At Hurghada, nine seaweed species (*Padina boryana*, *Digenea simplex*, *Sargassum cinereum*, *Galaxaura marginata*, *Halimeda tuna*, *Laurencia majuscula*, *Dictyopteris acrostichoides*, *Cystoseira indica* and *Caulerpa racemosa*) and two seagrasses species (*Halophila stipulacea* and *Halodule pinifolia*) were collected (Supplementary Table 2). As shown in Table 6, *L. majuscula* was the highest accumulator for Fe, Mn and Zn (1848.39, 153.10 and 85.00 µg g^{-1}, respectively). *P. boryana* was found to be the best scavenger for Ni (25.25 µg g^{-1}) and *S. cinereum* for Pb (13.50 µg g^{-1}). Cu bioaccumulation was nearly equal in 4 seaweed and seagrass species: *C. racemosa*, *H. pinifolia*, *H. tuna* and *L. majuscula* (11.90, 10.90, 10.80 and 9.20 µg g^{-1}, respectively). The highest Cd bioaccumulation was recorded in *L. majuscula* (2.65 µg g^{-1}). In conclusion, the studied species showed different tendencies towards the different metals, with significant responses from *L. majuscula* and *P. boryana*.

Three species of seaweeds (*Padina boryana, Galaxaura marginata* and *Halimeda tuna*) and two seagrass species (*Halophila stipulacea* and *Halodule uninervis*) were collected in the extreme conditions

Table 5

Mean concentrations of heavy metals in marine flora (µg g^{-1} dry wt.) at Ras Gharieb during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Digenea simplex*	1615.29 ± 133.08	66.95 ± 4.51	24.4 ± 2.74	5.00 ± 1.52	14.75 ± 2.41	15.05 ± 1.52	0.25 ± 0.09
	Sargassum cinereum	913.60 ± 120.71	29.40 ± 6.71	31.60 ± 3.64	1.35 ± 0.64	7.00 ± 1.29	BDL	2.20 ± 1.42
	Coralline berteroi	1000.65 ± 95.14	28.00 ± 2.64	25.75 ± 8.47	5.10 ± 0.83	2.10 ± 0.55	2.70 ± 0.08	1.40 ± 0.44
	Galaxaura marginata	1067.00 ± 109.35	42.95 ± 4.81	30.35 ± 6.19	6.70 ± 0.99	2.45 ± 0.84	2.90 ± 0.03	0.90 ± 0.01
Summer	*Halodule pinifolia* (Seagrass)	335.35 ± 96.66	21.30 ± 3.62	19.20 ± 3.33	7.00 ± 0.59	1.40 ± 0.08	BDL	0.80 ± 0.007
	Sargassum cinereum	285.15 ± 86.24	9.50 ± 0.63	9.10 ± 1.63	5.45 ± 1.26	4.75 ± 0.41	1.50 ± 0.05	0.35 ± 0.001
	Padina boryana	2673.90 ± 250.17	188.35 ± 12.31	68.45 ± 6.53	28.70 ± 4.15	50.75 ± 1.00	13.85 ± 2.14	2.05 ± 0.94

* BDL: below detection limit

Table 6

Mean concentrations of heavy metals in marine flora (µg g^{-1} dry wt.) at Hurghada during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Laurencia majuscule*	1848.39 ± 124.23	153.10 ± 4.88	85.00 ± 1.00	9.20 ± 2.41	4.90 ± 0.20	7.35 ± 1.82	2.65 ± 0.15
	Halimeda tuna	1401.90 ± 133.01	23.40 ± 1.21	15.15 ± 1.11	3.45 ± 0.31	5.05 ± 0.61	7.50 ± 0.15	1.55 ± 0.05
	Halophila stipulacea (Seagrass)	595.90 ± 21.56	36.95 ±1.45	24.25 ± 2.14	4.30 ± 0.52	13.30 ± 1.23	BDL	1.65 ± 0.03
	Dictyopteris acrostichoides	1202.70 ± 85.78	28.25 ± 1.75	23.75 ± 0.12	4.45 ± 0.21	BDL	BDL	1.75 ± 0.07
	Cystoseira indica	858.45 ± 65.19	27.60 ± 2.19	19.15 ± 0.22	1.30 ± 0.08	2.70 ± 0.33	2.25 ± 0.44	1.05 ± 0.01
	Halodule pinifolia (Seagrass)	1070.05 ± 101.22	28.35 ± 1.26	24.60 ± 2.10	6.30 ± 1.11	11.30 ± 0.55	BDL	0.30 ± 0.002
	Digenea simplex	1413.75 ± 98.77	57.15 ± 3.18	16.05 ± 3.11	2.55 ± 0.41	13.8 5± 0.54	0.65 ± 0.009	1.85 ± 0.51
Summer	*Sargassum cinereum*	343.40 ± 25.31	11.90 ± 1.25	6.30 ± 1.02	1.05 ± 0.21	7.55 ± 1.07	13.50 ± 2.35	1.40 ± 0.51
	Galaxaura marginata	853.05 ± 30.15	61.55 ± 6.25	16.50 ± 2.11	5.30 ± 0.91	4.80 ± 1.26	BDL	1.25 ± 0.62
	Padina boryana	1734.52 ± 119.98	98.55 ± 8.71	14.10 ± 0.81	4.25 ± 0.23	25.25 ± 3.21	11.90 ± 2.13	1.85 ± 0.19
	Halimeda tuna	499.70 ± 121.30	16.20 ± 3.21	8.45 ± 0.61	10.80 ± 4.61	4.80 ± 1.02	6.95 ± 1.45	0.90 ± 0.003
	Caulerpa racemosa	596.50 ± 97.26	21.80 ± 2.61	7.65 ± 1.43	11.90 ± 2.03	7.50 ± 1.46	2.40 ± 0.24	0.95 ± 0.007
	Halodule pinifolia (Seagrass)	985.00 ± 140.85	35.65 ± 4.51	21.8 ± 3.21	10.90 ± 1.41	7.80 ± 2.13	0.35 ± 0.06	0.45 ± 0.008

* BDL: below detection limit

of the Safaga tidal flat (Supplementary Table 2), where *P. boryana*, *H. stipulacea*, *G. marginata* and *H. uninervis* were found to have nearly equal high Fe bioaccumulation (1293.20, 1197.65, 1160.45 and 1074.10 µg g^{-1}, respectively). *G. marginata* was the highest accumulator species for Mn, Zn, Cu, Ni and Pb (88.70, 48.20, 18.75, 24.45 and 17.70 µg g^{-1}, respectively), while Cd was found in nearly equal amounts in most species (Table 7). Generally, seaweeds have a much more effective ability of heavy metal bioaccumulation than seagrasses, and the species collected in our study have adaptable mechanisms to survive under even extremely polluted conditions.

Additionally, the presence of *Chaetomorpha crassa*, *Ulva lactuca* and *Cladophora sp.* was a great indication of subsurface wastewater seepage at the Qusier tidal flat. Two seaweeds (*Padina boryana* and *Sargassum cinereum*) and two seagrasses (*Halodule pinifolia* and *Halophila stipulacea*) were recorded there (Supplementary Table 2). These flora species showed a high degree of adaptability. *P. boryana* was the highest bioaccumulator species for Fe, Mn and Zn (2589.64, 169.85 and 63.30 µg g^{-1}, respectively), while *H. pinifolia* was the highest accumulator for Ni (53.00 µg g^{-1}). The highest accumulation of Pb was found in *Cladophora sp.* (12.70 µg g^{-1}) while, *S. cinereum* was the highest accumulator for Cd (5.00 µg g^{-1}) (Table 8).

The wide range of heavy metal concentrations in different algal species reflects the importance of biochemical factors in affecting the relative tendency of different tissues to concentrate pollutants. Such biochemical or physiological differences may also play a major role in causing certain species to concentrate pollutants to a much higher degree than other organisms, regardless of the species' relative position in the aquatic food chain (Steele et al. 2001). The bioaccumulation of Fe, Mn, Cu and Cd measured in the seaweeds and seagrasses at the megacity sites were lower than those reported by Kannan et al. (1992), Thangaradjou et al. (2013) or Thangaradjou et al. (2010) and higher than those reported by Al-Shwafi & Rushdi (2008), Dadolahi-Sohrab et al. (2011) or Qari and Siddiqui (2010) for most metals except Fe.

4. Conclusions

In conclusion, our findings demonstrate that Fe levels in seawater can fluctuate between 7.86 and 27.95 µg l^{-1}, which is much higher than those recorded in

Table 7

Mean concentrations of heavy metals in marine flora (µg g^{-1} dry wt.) at Safaga during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Halophila stipulacea* (Seagrass)	1197.65 ± 85.46	61.10 ± 2.45	37.95 ± 6.31	10.75 ± 1.28	2.30 ± 0.92	2.30 ± 0.09	1.40 ± 0.18
	Padina boryana	1293.20 ± 141.84	73.15 ± 3.85	44.00 ± 5.81	5.70 ± 2.91	BDL	3.75 ± 0.84	1.50 ± 0.16
	Halodule uninervis (Seagrass)	501.15 ± 110.21	24.35 ± 2.48	14.35 ± 0.73	3.55 ± 0.52	0.70 ± 0.008	9.30 ± 1.25	1.25 ± 0.14
Summer	*Galaxaura marginata*	1160.45 ± 221.03	88.70 ± 5.16	48.20 ± 13.38	18.75 ± 2.81	24.45 ± 11.21	17.70 ± 3.06	1.05 ± 0.006
	Halimeda tuna	528.95 ± 75.24	32.90 ± 4.61	22.00 ± 4.61	8.90 ± 1.74	0.10 ± 0.001	3.45 ± 0.22	0.40 ± 0.007
	Halodule uninervis (Seagrass)	1074.10 ± 126.15	24.10 ± 2.55	22.75 ± 5.81	7.90 ± 3.91	19.70 ± 1.51	6.65 ± 0.81	0.90 ± 0.001

* BDL: below detection limit

Table 8

Mean concentrations of heavy metals in marine flora (µg g^{-1} dry wt.) at Qusier during winter and summer

Season	Specimen name	Fe	Mn	Zn	Cu	Ni	Pb	Cd
Winter	*Halodule pinifolia* (Seagrass)	1320.10 ± 201.14	23.90 ± 2.11	45.95 ± 17.24	15.50 ± 1.52	53.00 ± 5.55	3.95 ± 0.82	0.90 ± 0.12
	Cladophora sp.	2570.47 ± 165.41	151 ± 23.35	47.40 ± 6.22	15.80 ± 1.26	45.90 ± 12.33	BDL	2.15 ± 0.09
	Padina boryana	2589.64 ± 356.19	169.85 ± 19.24	63.30 ± 9.57	13.65 ± 2.71	35.35 ± 7.24	12.10 ± 1.21	21.00 ± 2.53
	Chaetomorpha crassa	1432.20 ± 221.03	26.15 ± 2.81	13.95 ± 1.45	2.50 ± 1.26	4.45 ± 1.01	4.00 ± 1.71	1.90 ± 0.07
	Ulva lactuca	1859.14 ± 195.46	50.15 ± 8.36	22.35 ± 3.62	5.95 ± 0.81	6.55 ± 1.28	BDL	1.60 ± 0.04
Summer	*Sargassum cinereum*	271.70 ± 94.51	7.60 ± 0.91	10.30 ± 0.92	5.95 ± 1.32	7.20 ± 0.37	BDL	5.00 ± 0.22
	Halophila stipulacea (Seagrass)	642.90 ± 136.46	29.35 ± 2.46	18.65 ± 0.94	23.55 ± 6.52	9.95 ± 1.24	BDL	1.00 ± 0.91
	Cladophora sp.	2517.63 ± 521.51	120.20 ± 35.19	54.25 ± 12.18	34.10 ± 3.42	44.90 ± 3.19	12.70 ± 2.14	1.25 ± 0.008

* BDL: below detection limit

most seas (0.06–0.17 µg l^{-1}), including the Arabian Sea. We found Zn concentrations (1.83–5.63 µg l^{-1}) that were within the normal range of the world's open oceans (~5 µg l^{-1}). In contrast, minuscule values of Mn, Cu, Ni, Pb and Cd were recorded in the seawater around the study sites. Regarding the fauna and flora collected in this study, Porifera species had a greater ability than others to accumulate most metals in their tissues. Also, seaweeds and seagrasses demonstrated a much greater adaptability than the benthic fauna in highly polluted regions, especially those with high turbidity, landfilling, sedimentation and high eutrophication.

Author Contributions

Salah-Tantawy conceptualised the research, collected samples, performed experiments and statistical analyses and wrote the manuscript. **Mahdy** and **Dar** contributed to the fieldwork, conceptualised the research and revised the manuscript. **Young** and **Abdelreheem** reviewed and revised the manuscript. All authors have read and approved the final manuscript.

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Supplementary Table 1

Marine benthic fauna collected from the study sites along the northern Red Sea during winter and summer

Phyla	Specimen name	Winter				Summer			
		Ras Gharieb	Hurghada	Safaga	Qusier	Ras Gharieb	Hurghada	Safaga	Qusier
Porifera	*Hyrtios protius*		√				√		
	Plakinastrella onkodes		√		√		√	√	
Cnidaria	*Stylophora pistillata*	√	√	√	√	√	√	√	
	Favites complanata		√		√				
	Favites abdita			√				√	
	Acropora polystoma		√				√		
	Acropora hemprichii						√		√
	Acropora clathrata				√				
	Acropora austera	√				√		√	
	Acropora pharoaonis			√					
	Acropora valida				√				
	Acropora humilis			√					
	Pocillopora verrucosa								√
	Pocillopora damicornis			√	√				
	Porites solida			√					
	Porites lobata						√		
	Porites mayeri				√				
	Favia maritima						√		
	Favia pallida				√				
	Ctenactis crassa				√			√	
	Galaxia fasciularis						√		√
	Millopora dichtoma				√				√
	Platygyra lamellina						√		
	Platygyra carnosus				√				
	Sarcophyton trocheliophorum	√				√			
	Tubipora musica						√		
	Dendronephthia hemprichi						√		
	Sinularia polydactyla						√	√	
	Heteroxenia fuscescens					√			
Mollusca	*Strombus triangulatus*	√	√				√		
	Tridacna maxima		√					√	
	Tridacna gigas						√		
	Murex tribulus		√					√	
	Tectus dentatus						√		
	Crassostrea sp.				√				
Echinoderms	*Astropecten irregularis*						√		
	Ophiocoma scolopendrina						√		
	Tripneaustus gratella		√						√
	Clypeaster audouini		√				√		
	Echinometra mathaei	√				√	√		
	Diadema setosum				√				

Supplementary Table 2

Marine benthic flora collected from the study sites along the northern Red Sea during winter and summer

Phyla	Specimen name	Winter				Summer			
		Ras Gharieb	Hurghada	Safaga	Qusier	Ras Gharieb	Hurghada	Safaga	Qusier
Seagrass	*Halophila stipulacea*		√	√					√
	Halodule uninervis			√				√	
	Halodule pinifolia		√		√	√	√		
Seaweed	*Halimeda tuna*		√				√	√	
	Cladophora sp.				√				√
	Chaetomorpha crassa				√				
	Ulva lactuca				√				
	Caulerpa racemosa						√		
	Padina boryana			√	√	√	√		
	Dictyopteris acrostichoides		√						
	Cystoseira indica		√						
	Sargassum cinereum	√				√	√		√
	Laurencia majuscula		√						
	Digenea simplex	√	√						
	Coralline berteroi	√							
	Galaxaura marginata	√					√	√	

Supplementary Table 3

Australian and New Zealand guidelines (ANZECC 1992; ARMCANZ 2000) for marine water quality (µg l^{-1})

Metals	Heavy metal limits in seawater (µg l-1) for a given level of protection of marine species			
	99%	95%	90%	80%
Zn	7	15	23	43
Cu	0.3	1.3	3	8
Ni	7	70	200	560
Pb	2.2	4.4	6.6	12
Cd	0.7	5.5	14	36

Supplementary Table 4

Concentrations of heavy metals in seawater at the study sites along the northern Red Sea in comparison with other studies in Egypt and worldwide

Site	Metal concentrations (µg l^{-1})							Reference
	Fe	Mn	Zn	Cu	Ni	Pb	Cd	
Ras Gharieb	7.86-26.10	0.02-0.12	2.05-2.77	0.81-1.54	0.40-1.74	BDL-0.92	0.24-0.09	Present study
Hurghada	9.73-22.14	0.07-ND	2.81-1.83	1.09-1.32	0.33-1.88	1.00-0.17	0.26-0.15	
Safaga	10.62-19.55	BDL-0.56	3.03-2.07	2.09-1.46	0.80-2.06	0.07-2.19	0.23-0.16	
Qusier	14.17-27.95	BDL-0.17	3.13-5.63	0.88-1.08	0.45-1.57	0.39-2.34	0.26-0.10	
Red Sea	1.21-1.77	0.10-0.16	0.16-0.27	0.11-0.15	0.11-0.16	0.25-0.37	0.23-0.59	Shriadah et al. 2003
Gulf of Aqaba	1.07-3.05	0.11-0.16	0.17-0.36	0.10-0.19	0.17-0.27	0.29-0.35	0.55-0.59	
Abu Shaar lagoon (Hurghada)	8.50-58.70	0.34-1.58	0.28-10.30	0.02-0.80	---	BDL-2.24	BDL-0.73	Abdel-Wahab et al. 2005
Safaga lagoon	24.83-66.96	0.97-1.75	1.55-10.67	0.54-2.42	---	0.11-1.26	0.07-0.25	
Shuni lagoon	5.14-44.94	BDL-1.50	2.28-3.97	0.20-1.46	---	0.30-0.98	BDL	
Abu Ghsoun lagoon	11.60-32.01	BDL-0.66	0.77-5.37	BDL-2.18	---	0.04-0.21	0.03-0.13	
Hurghada Harbor (Red Sea)	7.22-83.51	BDL-194	2.65-11.41	BDL-14.79	BDL-83	BDL-7.87	0.51-0.92	Madkour & Dar 2007
Northern Red Sea	9.10-28.35	---	7.18-15.21	2.08-5.23	2.33-5.80	0.37-0.80	0.13-0.43	Ali et al. 2011
Hurghada	---	0.80-15.92	0.12-43.11	0.01-10.66	---	0.14-46.52	0.11-1.11	Dar et al. 2016
Safaga	---	9.23-16.29	7.23-167.70	4.57-18.13	---	16.25-61.10	0.28-1.11	
Hamrawin	---	13.83-18.80	32.60-101.40	7.41-12.86	---	20.86-32.36	0.84-1.44	
Northern part of Red Sea	8.68-36.53	0.06-0.39	0.94-12.07	0.39-4.71	0.16-2.15	0.73-5.84	0.14-0.42	Abouhend & El-Moselhy 2015
Shalateen	2.02-15.15	0.09-1.20	3.28-9.34	0.89-2.59	---	1.43-3.46	0.14-0.63	El- Metwally 2015
Qulaan	5.93-22.14	0.26-1.15	1.03-6.22	0.61-1.48	---	0.44-2.10	BDL-0.37	
Abu Ghosoun	8.86-16.11	0.14-0.66	0.84-3.94	0.60-1.15	---	0.95-3.76	0.06-0.46	
Abu Dabab	8.19-13.07	0.05-0.78	1.50-4.54	0.56-2.14	---	0.76-1.94	0.02-0.53	
Sharm Al Bahari	11.31-24.02	0.09-0.75	1.74-11.57	0.65-1.95	---	0.65-2.83	0.04-0.25	
El-Hamrawin	7.48-16.67	0.14-0.97	1.38-16.68	0.61-2	---	1.34-2.66	0.13-0.41	
Sharm ElNaqa	6.64-11.31	0.12-0.65	1.39-3.53	0.59-2.13	---	0.29-2.18	0.07-0.14	
Hurghada	8.83-15.30	0.12-0.75	2.34-3.38	0.83-2.18	---	1-3.38	0.04-0.27	
Ras Gharieb	9.65-18.30	0.11-0.63	1.11-7.93	1.11-2.05	---	0.81-4.14	0.07-0.29	
Suez	13.16-51.96	0.13-1.04	3.72-22.68	2.01-3.34	---	2.56-5.54	0.12-0.18	
(Oman Sea)	11.52-25.36	2.12-8.67	5.32-22.62	1.06-5.74	3.20-17.14	0.98-4.52	0.1-0.19	Bazzi 2014
South Australia n Coastline	176-348	6.5-157	14-67	0.9-64.20	0.3-1.90	0.4-55	0.13-0.80	Chakraborty et al. 2013
Persian Gulf	---	---	---	---	41-97.44	0.5-8.3	BDL-3.92	Rahmanpour et al. 2014
Gorgan bay, Iran	---	---	1.18-6.2	0.2-2.48	---	0.96-7.10	1-4.7	Raeisi et al. 2014
(Red Sea) KSA	2.78-6.34	0.05-0.128	0.12-0.67	0.05-0.12	0.86-1.46	0.17-0.63	0.017-1.09	Al-Wesabi et al. 2015

* BDL: below detection limit