Egypt. J. Chem. **Vol. 67**, No.2 pp. 543 - 553 (2024)

Egyptian Journal of Chemistry

http://ejchem.journals.ekb.eg/

Sediment concentrations of heavy metals in the Bardawil Lagoon (Eastern Mediterranean Sea): Assessment of contamination and ecological risks

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Abstract

Bardawil Lagoon is one of Egypt's most notable coastal Mediterranean lakes. This research looks at the prevalence and risk of heavy metals in sediments. In all, eight locations around Bardawil Lake were chosen to collect sediment samples. The following is a ranking of the measured mean concentrations of heavy metals in the examined lagoon. The order is Fe > Mn > Cu > Zn > Pb > Cd > Cr > Ni. Ecological risk was evaluated in sediment using single and multi-elemental standard indices. Metals were ordered from highest to lowest based on their mean enrichment factors (EF): Cd > Pb > Cu > Mn > Zn > Cr > Ni. The geoaccumulation index (Igeo) values for Cd over the studied area varied widely, from clean to moderately polluted too extremely contaminated. The bulk of the sites had DC values below 32 (i.e., substantial DC), with the greatest values found at sites 1, 4, and 10. The highest average DC values were 47.39, 45.70, and 50.95. Cd > Pb > Cu > Mn > Zn > Ni > Cr; these are the heavy metals with the highest to lowest mean values of the ecological risk factor (Er). Possible ecological risk index (PERI) values varied from 445.13 at site 7 to 1441.93 at site 10. Reducing the buildup of heavy metals in Bardawil Lake will require cutting-edge treatment technology and careful monitoring of contamination in the lake's water and sediments.

Keywords: Heavy metals; pPollution indices; Bardawil Lagoon, Environmental hazard.

1. Introduction

Heavy metals are abundant in all ecosystems since they are a part of the Earth's crust, but their concentrations have been considerably increased as a result of human activities [1,2]. As a result, over the past 20 years, there has been a lot of focus on understanding the harmful impacts of trace metals on various ecosystems. Coastal ecosystems are vulnerable to heavy metal pollution due to inputs from primary natural, industrial, and urban sources as well as air deposits transmitted via river discharge, oceanic dumping, and eolian processes [3,4]. For environmental and geochemical studies on marine contamination, marine sediments typically offer useful information. On the surfaces of fine particles, heavy metals, insecticides, and other harmful compounds may be absorbed from the water column and typically migrate with the sediments [5]. For these xenobiotics, sediments can serve as a true "sink," facilitating the analytical determination of their concentrations and providing time-integrated data on the ecosystem's health [6].

Greater social, economic, and ecological value is placed on Egypt's northern coastal region in the world, which include the lakes and wetlands ecosystems. There are five lakes in Egypt's lake regions along the Mediterranean coast. Mariout, Edku, Burullus, and Manzala are the four deltaic lakes, whereas Bardawil Lake is the sole non-deltaic lake [7, 8]. Egypt's fast population increase, especially in the Nile Delta's wetlands, causes water

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EJCHEM use only: Received date here; revised date here; accepted date here.
DOI: 10.21608/EJCHEM.2023.215077.8080

pollution and land reclamation, which degrade and reduce healthy water sources. Thus, protection of these water bodies is crucial for their better management, especially for the Egyptian economy and public health [9].

Along Egypt's Mediterranean coast lies the large wetland known as Bardawil Lagoon. The vast part of Bardawil Lagoon consists of a flat, low-lying plain. A defining feature of the north Sinai coast, its circular shape is a product of geography. It is separated from the Mediterranean by a long, convex sand bar. The main body of water in the lake is located to the east, along a strip of shoreline that reaches a terminus not far from Zaranik Pond. The latter is a crucial step in the salt-making process (locally, it is called Malahat Sebikah) [10, 11]. Productivity per feddan clearly fluctuated throughout time, as seen by shifts in both gross fish output and the volume of water in the lake. Bardawil now hosts an increasingly vital fishing industry. While it is well recognized as a prime fishing spot in Egypt, its 2005 yield of 3,534 tons represented only 0.7% of the country's overall catch [12].

There are fewer water currents between near-shore areas and the estuaries and coastal lagoons that often absorb runoff from inland human activities [13]. To develop effective remedial measures for metal pollution [14-16], it is important to determine the extent to which trace metals have contaminated sediment and to distinguish between natural and anthropogenic sources. Estuaries and lagoons are some of the most productive marine ecosystems in the world, serving as feeding, migrating, and nidification grounds for a wide variety of organisms. Heavy metal ions (HMIs) in the environment may have devastating effects on ecosystems, human health, and other forms of life. Due to rising worries about the impact of industrialization on the environment, new tools have been developed to identify and monitor HMIs. To better understand the environmental risk in Bardawil Lagoon, we set out to (i) quantify the concentrations of eight different heavy metals (Mn, Cu, Ni, Cr, Fe, Co, Cd, and Pb) and (ii) apply several pollutant indicators.

2. Materials and Methods

2.1. Description of the Study Site

Bardawil Lagoon stretches along the northern shore of Sinai, beginning about 45 km east of Port Said and ending about 20 km west of El-Arish. Its eastern and western boundaries are at 32°41′00″ and 33°30′00″ of longitude, and at 31°03′00″ and 31°14′00″ of latitude. Its northern border is formed by the Sinai Mediterranean coast, its southern border by a sand dune belt that juts inland to the fold and anticlinal hills, its western border by the Tineh Sabkha flat, which forms the eastern edge of the Nile Delta plain, and its eastern border by the Arish-Rafah sector (Figure 1). This lake has a maximum depth of 80 kilometers and a surface area of about 164,000 feddan (about 685 km2). Bardawil has a maximum depth of roughly 3 m and a breadth of about 20 kilometers. A lengthy convex sand bar separates it from the Mediterranean. The lake's primary body of water is located to the east along a part of the shoreline that is roughly 30 km long and ends at Zaranik Pond (has an area of about 58,000 feddan, of which Zaranik Pond occupies about 10,000 feddan).

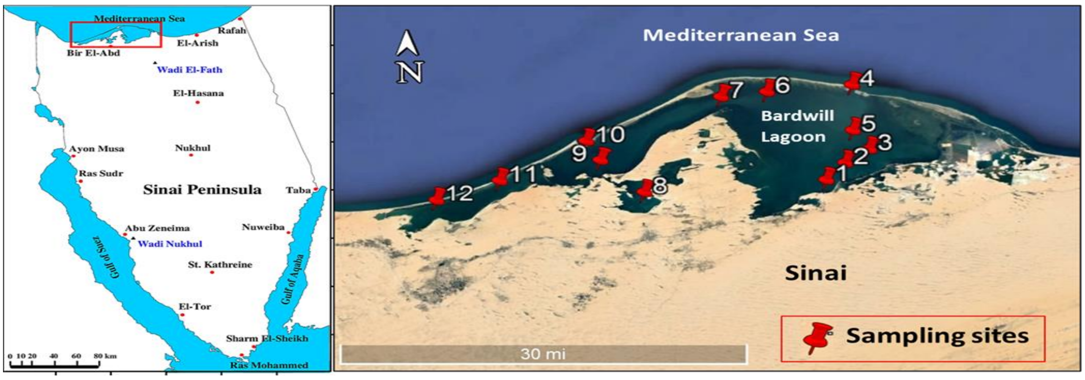

Figure 1. Location map of Egypt, and Bardawil Lagoon showing sampling sites in North Sinai.

2.2. Sample Collection and Preparation

Composite sediment samples (n = 3) were obtained from each location in the spring of 2022. Table 1 displays twelve geographically related displays of the Bardawil Lagoon. All samples were quickly transferred in plastic bags to the lab following collection. The materials were thoroughly combined, air-dried, sieved using a 2-mm sieve to remove stones and other debris, and stored in plastic bags until analysis could be performed.

Table 1. Coordinates and description of sampling sites in Bardawil Lagoons.

Site No	N	E	Description
S1	31.07694	33.22667	El- Telol
S2	31.09944	33.25083	El-Rodh
S3	31.11750	33.28083	El-Zarnik
S4	31.20417	33.26139	Boughaz 2
S5	31.14306	33.26111	M. El-Telol
S6	31.19639	33.15556	Masqut-Eplis
S7	31.19056	33.09833	El-Gals
S8	31.06389	33.00056	El-Rewak
S9	31.10778	32.94694	N. El-Rewak
S10	31.13361	32.92972	Boughaz 1
S11	31.08194	32.82139	El-Nasr
S12	31.05667	32.74250	Raba'a

2.3. Metal analysis of sediments

Chemical analysis came after acid extraction by microwave digestion (AR-MW) [17]. Each sample of silt (0.2 g) was put in a Teflon container with 12 mL of a 37% HCl:70% HNO3 (3:1) solution. The microwave oven reached 180 °C in 5.5 minutes and maintained that temperature for another 9.5 minutes, adequately heating the pots. The concentrations of eight metals (Fe, Mn, Zn, Cu, Cr, Ni, Cd, and Pb) in sediment were determined using a standard calibration procedure and an inductivity-coupled plasma optical emission spectrometer (Thermo ScientificTM iCAPTM 7000 Plus Series ICP-OES, USA). ICP-OES wavelengths were chosen in accordance with ISO [18]. When Certified Reference Materials (CRM) were compared to stock standard solutions of Fe, Mn, Zn, Cu, Cr, Ni, Cd, and Pb from Merck in Darmstadt, Germany, it was found that the elemental analysis was correct.

2.4. Assessment of Sediment Heavy Metals Contamination

Enrichment factor (Ef), contamination factor (Cf), geoaccumulation index (Igeo), ecological risk factor (Er), degree of contamination (Dc), and prospective ecological risk index (PERI) [19-24] were used to quantify pollution for each metal along the drains. Tables 2 and 3 detail the formulae for determining pollution index values and the associated class thresholds.

Table 2. Various pollution indices formulas used in the present study.

Index	Formula	References
Enrichment factor (E*f*)	$EF = \left(\frac{C_{sample}}{Fe_{sample}}\right) / \left(\frac{C_{ref}}{Fe_{ref}}\right)$	Franco-Uria et al. [22]
Contamination factor (C*f*)	$CF = C_{sample} / C_{ref}$	Hakanson [21]
Geoaccumulation index (I*geo*)	$Igeo = Log2 \left(\frac{C_{sample}}{1.5Bn}\right)$	Muller [24]; Lu and Bai [23]
Ecological risk factor (E*r*)	$Er = Ti * Cf$	Hakanson [21]
Degree of contamination (D*c*)	$Dc = \sum_{i=1}^{n} CFi$	Hakanson [21]; Caeiro et al. [19]
Potential ecological risk index (PERI)	$PERI = \sum_{i=1}^{n} ER$	Kowalska et al. [20]

Abbreviation: C_{sample}: metal concentration in soil analyzed sample; Fe_{sample}: concentration of the reference metal in soil analyzed sample; C_{ref} : (background) metal concentration in the reference environment; Fe_{ref} (background), reference metal concentration in the reference environment; Bn: the geochemical background value in average shale of element *n*; 1.5: the background matrix correction due to terrigenous effects; Ti: the toxic-response factor for a given substance; Cf: the contamination factor.

Table 3. Classes of used indices for metals in the present study.

E*f*		I*geo*	
Classes	**Sediment quality**	**Classes**	**Sediment quality**
EF < 2 = natural, EF > 2 = anthropogenic		I*geo* ≤ 0	Uncontaminated
Ef < 1	Depletion or no enrichment	0 < I*geo* < 1	Uncontaminated to moderately contaminated
Ef < 2	Minor enrichment	1 < I*geo* < 2	Moderately to heavily contaminated
Ef = 2-5	Moderate enrichment	2 < I*geo* < 3	Moderately to strongly contaminated
Ef = 5-10	Moderately severe enrichment	3 < I*geo* < 4	Strongly contaminated
Ef = 10-25	Severe enrichment	4 < I*geo* < 5	Strongly to extremely contaminated
Ef = 25-50	Very severe enrichment	I*geo* > 5	Extremely high contaminated
Ef > 50	Extremely severe enrichment		
C*f*		D*c*	
Classes	**Sediment quality**	**Classes**	**Sediment quality**
CF < 1	Low contamination factor	DC < 8	Low DC
1 ≤ CF ≤ 3	Moderate contamination factor	8 ≤ Dc < 16	Moderate DC
3 ≤ CF ≤ 6	Considerable contamination factor	16 ≤ Dc < 32	Considerable DC
6 ≤ CF	Very high contamination factor	Dc > 32	Very high
E*r*		PERI	
Classes	**Sediment quality**	**Classes**	**Sediment quality**
Er < 40	Low ecological risk	PERI < 150	Low risk
40 ≤ Er < 80	Moderate ecological risk	150 ≤ PERI < 300	Moderate
80 ≤ Er < 160	Considerable ecological risk	300 ≤ PERI < 600	Considerable
160 ≤ Er < 320	High ecological risk	PERI ≥ 600	Very high.
Er ≥ 320	Very high ecological risk		

Abbreviation: Enrichment factor (EF), Contamination factor (CF), Degree of contamination (Dc), Geoaccumulation index (I*geo*), Ecological risk factor (Er) and Potential ecological risk index (PERI)

2.4. Data Treatments

COSTAT 6.3 was used to analyze sediment analysis data and separate mean values using the least significant difference (LSD) at the 0.05 probability level. Pearson correlation bivariate two-tailed test was employed in SPSS 16 for Windows to determine if sediment parameters differed significantly across research locations.

3. Results and Discussion

3.1. Heavy Metals in Sediment

Heavy metals are any group of metals that exist in the Earth's crust at a relatively high concentration. Human actions elevate heavy metal levels in ecosystems, which in turn increases pollution and the danger to human health [25, 26]. We discovered the following order for the mean concentrations of the heavy metals we tested for in the examined lagoon: Fe is superior to Mn, Cu, Zn, Pb, Cd, Cr, and Ni. The present findings show that the sequence of heavy metals in the sediments of Idku Lake is as follows, when compared to other Egyptian coastal lakes, such as those studied by El-Amier et al. [27]. To rank them: Fe > Pb > Co > Cr > Cd > Ni. The mean concentrations of heavy metals in Burullus Lake are ranked by El-Alfy et al. [28] as follows: Mn > Fe > Zn > Co > Cu > Cd > Ni > Pb > Cr. Core sediment samples from Burullus Lake showed the following concentrations of heavy metals on average: Mn > Zn > Ni > Cu > Pb > Co > Cd, as reported by El-Amier et al. [27].

Iron is the most prevalent element, with sediment concentrations ranging from 6191.16 µg/g in site 12 to 17432.89 µg/g in site 8 with a mean of 11085.61 µg/g (Table 2). Fe is a ubiquitous element that is the third most abundant in the Earth's crust (after silicon and oxygen) [29, 30]. Fe concentrations in running water are affected by anthropogenic activities like steel production and sewage disposal. Iron sulfate is also used in the production of fertilizers and pesticides [31]. The manganese content followed the iron concentration, lending credence to Farhat's theory that the two elements are linked in a geological cycle [29].

The mean values of Mn, Zn, Cr, and Ni are 264.86 g/g, 26.88 g/g, 4.44 g/g, 2.71 g/g, respectively; however, the greatest concentrations of the measured metals were found in site 3. The concentrations of these elements varied from 187.36 µg/g in site 11 to 489.57 µg/g ,19.63 µg/g in site 5 to 37.84 µg/g, 1.61 µg/gin site 7 to 9.09 µg/g, and 1.17 µg/g in site 7 again to 5.75 µg/g (Table 2). These levels are within the permissible limits recommended by the US EPA [32]. Although manganese is a necessary metal for plant growth, too much of it in the soil might inhibit plant growth because it competes with other cationic elements for transport and metabolism. The Mn level in the study was within the range that most plants can tolerate [33]. Zn can settle in soil and water and is typically brought into aquatic ecosystems through the atmosphere. In addition, the presence of slat pan companies, new construction projects, national highways, solid waste burning, aquaculture businesses, agricultural practices, etc. could be sources of Zn. An additional source of zinc is found in herbicides and fungicides that contain zinc sulfate.

The highest values of Cu, Cd, and Pb were recorded in site 10 of the studied lagoon, where their levels ranged from 52.29 to 20.63 µg/g in site 11, 14.28 to 4.37 µg/g in site 7 and 29.88 to 10.82 µg/g in site 3, respectively. The mean values of the measured metals are 30.44, 8.01, and 14.58 µg/g, respectively (Table 2). Human activities, including fungicidal treatments, mining, sewage sludge, and particle pollution from automobile brakes, are common sources of Cu contamination [34]. The majority of Cu and Ni readings are linked to carbonates, organic compounds, and Fe/Mn oxides [35]. Anthropogenic output, such as automotive exhausts and car batteries, industrial effluents, sewage sludge, fertilizers, and pesticide application, has been shown to be the primary source of Pb in several studies [36, 37]. US-EPA [32] found only an average Cu value at the high end of the spectrum, whereas EU [38] and CSQGD [39] found an average Cd value at the high end of the spectrum.

Table 2. The concentrations of heavy metals of the sediment samples at different sites in Bardawil Lagoon during four seasons.

No of sites	Heavy metal in (µg/g)							
	Fe	Mn	Cu	Zn	Cd	Cr	Ni	Pb
1	15250.14	222.45	44.34	27.94	13.34	4.6	2.51	19.38
2	12765.99	263.41	27.62	23.96	4.55	4.05	2.39	15.47
3	16632.08	489.57	30.45	37.84	6.23	9.09	5.75	10.82
4	11974.68	247.15	26.09	35.69	13.04	2.69	1.64	13.63
5	9189.42	229.71	24.05	19.63	9.85	3.19	1.93	11.62
6	9567.72	198.63	24.57	20.6	5.46	4.37	2.6	10.85
7	10236.41	241.88	32.3	24.91	4.37	1.61	1.17	15.51
8	17432.89	456.89	21.36	34.55	6.81	5.64	3.45	12.15
9	9278.61	200.65	30.79	28.98	4.82	4.49	2.69	12.72
10	7612.84	196.22	52.29	23.91	14.28	2.34	1.52	29.88
11	6895.35	187.36	20.63	24.41	8.09	5.78	3.53	11.97
12	6191.16	244.4	30.74	20.08	5.28	5.41	3.3	10.94
Mean	11085.61	264.86	30.44	26.88	8.01	4.44	2.71	14.58
SD	3759.46	100.41	9.32	6.24	3.70	1.98	1.22	5.44
p-value	5.48***	2.91**	1.24^{ns}	1.30^{ns}	1.30^{ns}	3.20**	2.98**	0.50^{ns}
Permissible limits worldwide								
EU (2002)	-	-	300	300	3	150	75	300
CSQGD (2007)	-	-	70	-	1.4	64	50	70
US EPA (1999)	-	550	19	60	0.01–41	54	19	19
Average Shale	-	1	5	1	30	2	5	5
Toxic response factor	-	-	300	300	3	150	75	300

SD: standard deviation; different superscript letters within each column mean values significant at $p \leq 0.05$; EU: European Union Standard (2002); CSQGD: Canadian soil quality guidelines for the protection of environmental and human health document (2007); US EPA (United States Environmental Protection Agency) (1999). ***: significant at $p \leq 0.001$, **: significant at $p \leq 0.01$, *: significant at $p \leq 0.05$, ns: non-significance.

3.2. Correlation Coefficient Analysis of Heavy Metals

High degrees of association between heavy metals in sediments may be indicative of similar contamination and/or pollution discharge from the same sources [48]. Pearson's correlation coefficient (r) was used to examine the relationship between the various metals present in the region. All significant positive correlations ($p < 0.01$ or $p < 0.05$) were found between different pairings of heavy metals. It was discovered that Fe was correlated with Mn and Zn (r = 0.779, 0.744, respectively). Furthermore, Mn was well correlated with Zn, Cr, and Ni (r = 0.705, 0.655, and 0.688, respectively). There was a correlation of both Cu and Cd with Pb (r = 0.880, 0.631, respectively), and Cr was correlated with Ni with r = 0.994, as shown in Table 4. El-Amier et al. [40] found similar patterns in Mediterranean Sea drain estuary sediments, while Bessa et al. [41] found similar patterns in Atlantic Ocean beach sands, corroborating our findings.

Sand has a negative correlation with heavy metal concentrations, whereas silt, clay, and OM all have positive correlations. Engel et al. [42] report that when organic materials are exposed to heavy metals, powerful molecules are generated. Xiao et al. [43] shown that when sediment pore size is reduced, heavy metal concentrations rise.

Table 4. The Pearson correlation between the concentrations of heavy metals.

	Fe	Mn	Cu	Zn	Cd	Cr	Ni	Pb
Fe	1							
Mn	0.779**	1						
Cu	-0.067	-0.238	1					
Zn	0.744**	0.705*	-0.074	1				
Cd	0.025	-0.227	0.537	0.135	1			
Cr	0.411	0.655*	-0.274	0.424	-0.298	1		
Ni	0.396	0.688*	-0.279	0.442	-0.324	0.994**	1	
Pb	-0.116	-0.303	0.880**	-0.109	0.631*	-0.475	-0.472	1

* $p < 0.05$, ** $p < 0.01$; significant correlations (two-tailed).

3.3. Contamination Assessment of Heavy Metals in Sediment

The ecological risk index is suggested to characterize the translocation of heavy metals in soils and plants [44], and it is used as a tool for measuring the level of pollution in the environment. These indicators are also used to calculate the potential ecotoxicological and health hazards associated with consuming contaminated food crops. To lessen the health concerns, remediation techniques and efforts should focus on lowering metal concentrations in the soil [45].

3.3.1. Enrichment Factor (EF)

The effects of anthropogenic contamination on the content of heavy metals in sediments were evaluated using the EF. Iron was used in this experiment as the reference element for determining EF values [46]. The measured ranges of EF for Mn and Zn were the lowest at site 1 (0.81-0.91), respectively, while Mn highest value was at site 12 (2.19) and for Zn highest value was at site 11 (1.76), with a mean of 1.36 and 1.27, respectively. The EF for Pb ranged from 1.54 in site 3 to 9.26 in site 10, and the mean was 3.48. The enrichment factor for the Cr metal ranged between 0.08 at site 7 and 0.46 at site 12. The calculated ranges of EF for Cu and Cd were the lowest at site 8 (1.29 and 61.46, respectively), and the highest values were (7.20 and 295.12, respectively) at site 10, with a mean of 3.22 and 125.55, respectively. The Ni EF was 0.08 at site 7 and 0.37 at site 12, with a mean of 0.18. According to their EF mean values, the studied metals were ranked in the following order: Cd > Pb > Cu > Mn > Zn > Cr > Ni (Figure 2).

If the EF is between 0.05 and 1.50, all the heavy metals in the sample came from the crust and occurred naturally, and if it is greater than 1.50, the heavy metals came from non-crustal materials, like those produced by both point and non-point anthropogenic sources [46]. Metal bioavailability and toxicity in sediment samples are affected by both metal concentration and chemical form [47].

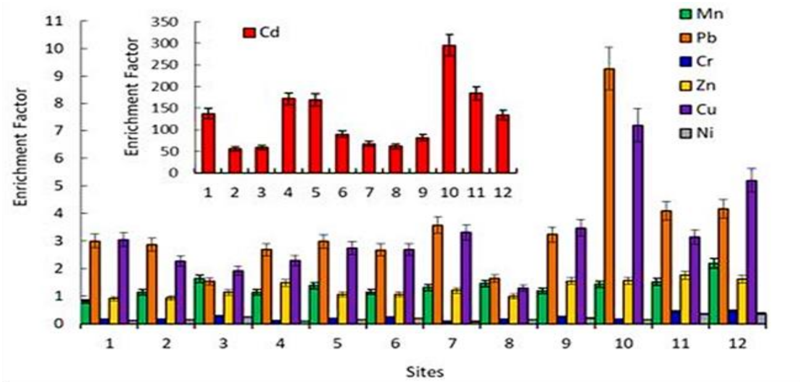

Figure 2. The heavy metals enrichment factor in the sediment samples from different sites

3.3.2. Geo-accumulation Index (Igeo)

It is generally agreed that the Igeo is the most accurate and extensively used index for quantifying metal loads in marine sediments. The Igeo was established by comparing the element's measured concentration to its geochemical background value in a typical shale [20]. Based on the present Igeo values for the examined metals, the sediment from the studied lagoon may be classified as class 0 (Igeo<1; i.e., uncontaminated; Fe, Mn, Pb, Cr, Zn, Cu, and Ni). Sites 7 and 2 have an Igeo value for Cd between 0 and 1, indicating low to moderate contamination, whereas the other sites in the study region have values between 1 and 2, indicating moderate to high contamination (Figure 3).

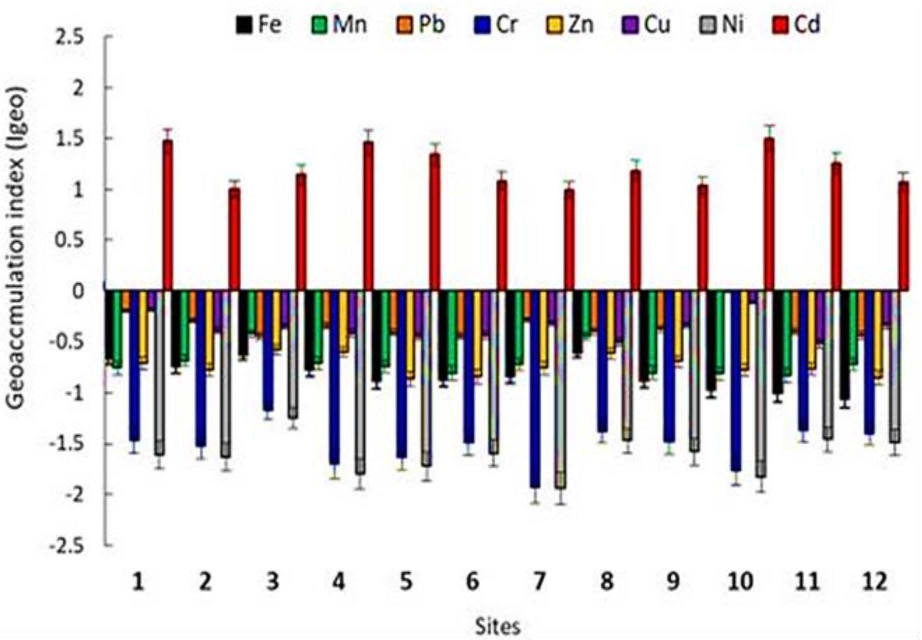

Figure 3. The geo-accumulation index of the heavy metals in the sediment samples from different.

3.3.3. Contamination Factor (Cf) and Contamination Degree (CD)

The contamination factor (Cf) provides for the evaluation of sediment contamination by considering the ratio of the metal content in the sample sediment (C_{sample}) to the metal concentration in the reference sediment (C_{ref}). Heavy metal contamination of soil is evaluated according to the abundance of different metals found in the planet's crust [21]. The current findings show that all sites except for site 10 (Cf = 1.16) have values of Cf for Pb, Cr, Zn, and Ni that are less than 1 (low contamination), but Cd values showed notable heterogeneity among the analysed sites, with the highest concentrations being observed.

From 14.57 at site 7 to 47.60 at site 10 (high contamination), the Cd contamination factor values fluctuated (Figure 4).

Additionally, the average degree of contamination (DC) revealed that, except for sites 1, 4, 5 and 10, which had values of 47.39, 54.70, 34.68, and 50.95, most of the sites had a DC of less than 32 (i.e., considerable DC) (Figure 4).

From the above results of the pollution indices, we have observed that Igeo showed the same tendency as Ef and Cf, indicating that Bardawil Lagoon is mostly uncontaminated (i.e., of natural origin), except for the moderate to heavy Cd and Pb contamination (i.e., of anthropogenic origin).

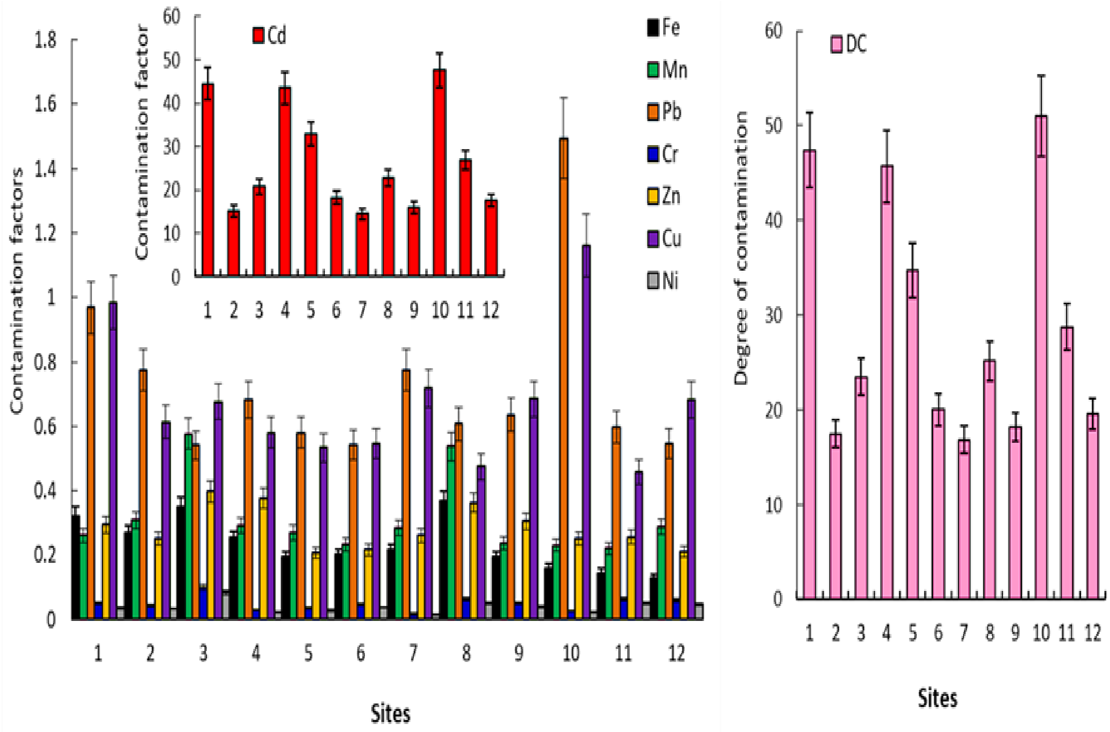

Figure 4. The contamination factors and degree of contamination of heavy metals in the sediment samples from different.

3.3.4. Ecological Risk Assessment

Heavy metals in the sediments were assigned an ecological risk index (Er) based on the prospective ecological risk index (PERI). The PERI was used to assess the ecological sensitivity of heavy metal pollution in stream sediments [21] based on the toxicity of the metals and the reactions of the environment.

It is possible to rank the heavy metals according to their mean Er values, as shown below. Cd is superior to Pb, Cu, Mn, Zn, Ni, and Cr. When compared to Cd's very high Er value of 801 (Er ≥ 320), the mean Er values of Mn, Pb, Cr, Zn, Cu, and Ni were all lower than 40 (Er < 40; i.e., minimal ecological danger). Cadmium, one of the most toxic heavy metals, may be found in cadmium shale at concentrations much beyond its geological background value. Site 7 had a PERI value of 445.13, whereas site 10 had a PERI value of 1441.93. Except for sites 2, 7, and 9 (462.76, 445.13, 489.44, and 535.01, respectively), the degree of sediment ecological damage was at significant to very high-risk levels (PERI ≤ 600) (Figure 5).

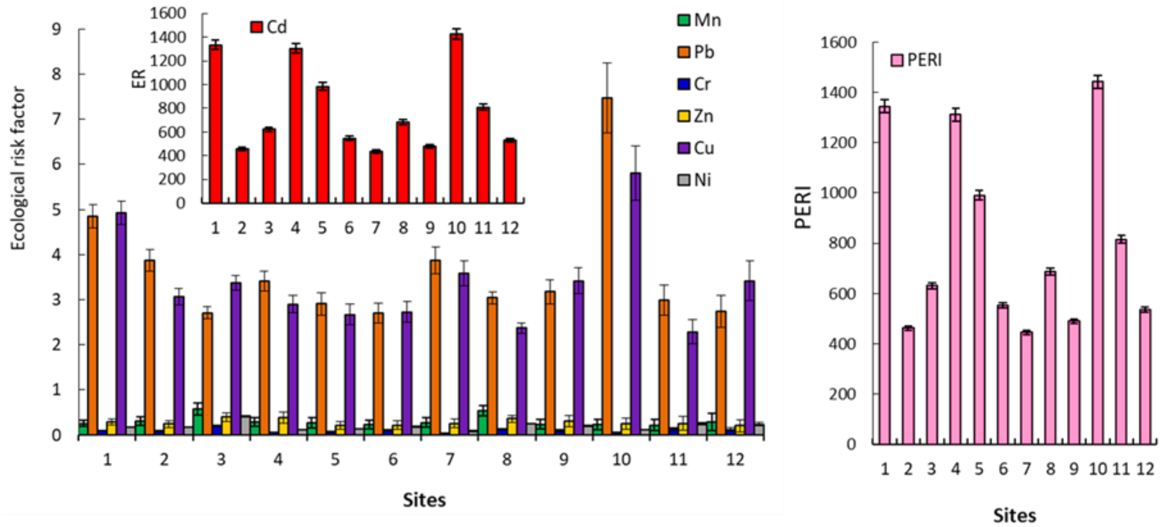

Figure 5. The Ecological risk factor and potential ecological risk index of heavy metals in the sediment samples from different.

4. Conclusions

- The order of metals is Fe > Mn > Cu > Zn > Pb > Cd > Cr > Ni.
- According to their EF mean values, the studied metals were ranked in the following order: Cd > Pb > Cu > Mn > Zn > Cr > Ni.
- Based on the metals' Igeo results, the lagoon's sediment is Igeo < 1 for Fe, Mn, Pb, Cr, Zn, Cu, and Ni (uncontaminated), while the Igeo value for Cd is 1 < Igeo < 2 (uncontaminated to moderately contaminated to strongly polluted).
- All sites except site 10 (Cf = 1.16) had Cf values of less than 1 (low contamination) for Pb, Cr, Zn, and Ni, however, Cd levels revealed significant variation.
- For the investigated heavy metals, Cd has the highest mean Er value, followed by Pb, Cu, Mn, Zn, Ni, and finally Cr.

5. Conflicts of interest

"There are no conflicts to declare".

6. Acknowledgments

"None"

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