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Ecological Risk Assessment of Heavy Metals in Water, Sediment and Macrophytes of Two Drains in the Deltaic Mediterranean Coast of Egypt

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ABSTRACT

Samples of water, sediment, and three aquatic plants, namely *Phragmites australis*, *Typha domingensis*, and *Eichhornia crassipes*, collected from ten stations were analyzed to estimate the pollution status with heavy metals in two drains (Kitchener and New Damietta) in the Nile Delta, Egypt. Ten indices were used to evaluate the ecological risk released by these metals. Results revealed high concentrations of Cu, Pb, and Cd in the Kitchener Drain water, while Fe was recorded in high concentrations in the New Damietta Drain water. Cu, Pb, Fe, and Cd were recorded to be within the Environmental Protection Agency (US-EPA) (2002) and World Health Organisation (2011) limits for water. A high concentration of Cu, Pb, and Fe was found in the New Damietta Drain sediment, while Cd was found in a high concentration in the Kitchener Drain sediment. Cu, Fe, and Cd were recorded to be within US-EPA (2002) limits for sediments, while Pb exceeded the permissible limits. *Eichhornia crassipes* accumulates higher concentrations of Cu, Pb, and Cd than the other plant species, while *Phragmites australis* exhibited the highest concentration of Fe. The study's plant species showed a decreased rate of metal translocation and distribution from their belowground tissues to their aboveground tissues, as indicated by the translocation factor values that were below one. As a result, the studied species accumulate heavy metals in their underground parts and do not effectively transfer metals from the belowground to the aerial parts. Thus, the examined species may be used to phytostabilize metal-polluted sediment as metal excluders.

INTRODUCTION

During the twenty-first century, critical challenges with water quality and quantity have been facing humanity. Because of anthropogenic activities and climate change, these challenges will get worse in the future (Parisi & Guerriero, 2019). Given the rapid population expansion, many nations, especially developing ones, reuse wastewater extensively for irrigation, and most frequently, they drop effluent discharge pipes into natural drainage systems **(Chaoua *et al*., 2019)**. The pollution of water is one of the most severe things that affects how vulnerable it is.

According to **Zhang *et al*. (2017)**, untreated wastewater from factories, drainage from municipalities, and runoff from chemicals such as pesticides and fertilizers used in agriculture are the main sources of pollution. Typically, industrial, agricultural, and municipal operations contribute several contaminants to the agricultural drainage water. All these activities pollute sediments and water bodies with significant amounts of heavy metals **(Förstner & Wittmann, 2012)**. Heavy metal pollutants have adverse effects on aquatic ecosystems because of their toxic effects, accumulation, and long environmental persistence **(Nabi & Dar, 2022)**.

From economic and ecological perspectives, using plants as purification systems in different aquatic ecosystems is garnering more attention **(Eid *et al*., 2020)**. The ability of macrophytes to effectively absorb contaminants from soils and waterways contributes significantly to the ecosystem's capacity to store vast amounts of metals in the plant's roots and/or aerial parts **(Dar *et al*., 2022)**. Phytoremediation is accomplished using a variety of techniques, including phytostabilization, phytoextraction, and rhizofiltration **(Saha *et al*., 2017)**. *Eichhornia crassipes* is one of these plants that is used for remediation in contaminated areas like streams, lakes, drains, and wastewater **(Adelodun *et al*., 2020)**. In a variety of habitats, *Phragmites australis* has been described as an effective phytoremediator for numerous heavy metals **(Bonanno, 2013; Cicero-Fernández *et al*., 2016)**. On the other hand, *Typha domingensis* has a high level of structural flexibility, which enables it to efficiently adapt to various environmental circumstances and eliminate heavy metals **(Hadad *et al*., 2010)**. These plants are eco-friendly, cost-effective, and sustainable methods for phytoremediation to remove heavy metals and recuperate nutrients from several kinds of municipal, manufacturing, and farming wastewater **(Haroon, 2022)**.

Anthropogenic activities have exposed two major drains (Kitchener and New Damietta) along Egypt's Nile Delta, which empties into the Mediterranean Sea to exponential and severe pollution. Heavy metal contamination has been caused by agricultural, industrial, and municipal pollutants in these drains **(Aitta *et al*., 2019)**. These drains are used for irrigation even though they have a significant pollutant load and do not meet legal requirements **(EEAA, 2008)**. The use of drainage water for irrigation in the agro-system must be restricted due to the high levels of pollutants to avoid dangers to the soil, the yield and performance of crops, and the wellness of the public. Three perennial aquatic macrophytes (*Eichhornia crassipes*, *Phragmites australis* and *Typha domingensis*) were chosen for this study with the intention of evaluating their phytoremediation capability. The objectives of the present work were: (i) evaluation of the pollution status by some heavy metals (Cu, Fe, Pb, and Cd) in the two main drains; (ii) evaluation of the risk to the ecosystem along both drains using various pollutant indices; and (iii) evaluation of the three macrophytes' phytoremediation capacities for the heavy metals under investigation in order to estimate their environmental risk.

MATERIALS AND METHODS

1. Study area

The present research was conducted on the Kitchener and New Damietta drains (Fig. 1). Kitchener Drain starts north of Tanta City in the Gharbia Governorate and proceeds north through Kafr El Sheikh Governorate until it ends at Baltim City and the Mediterranean Sea. It lies 10 kilometers east of Burullus Lake's outlet, a UNESCO-protected region. The drain is 47km long, 40 to 53m wide, and 5 to 6.m deep in Kafr El-Sheikh Governorate. According to **El-Gammal (2016)**, its total area of catchment is roughly 472,500 acres. It is located on the Mediterranean Sea shore in an area with low topographic relief. The drain's discharge ranges between 20 and 80m^3 per second. Twelve pumping plants release a total of 46,446,250 m^3 of initial treated wastewater into the drain each year before it reaches Burullus Lake. Drainage water is therefore tainted with minerals and chemicals used in agriculture (heavy metals and pesticides) in addition to pathogenic organisms from residential sources **(Gad & Fadi, 2015)**.

The New Damietta drain is located in New Damietta City, Egypt, where agricultural, industrial, and municipal debris are all received in large quantities. Industries located in the zone generate different types of wastewater. These industries do not pre-treat their wastewater before it is combined with municipal waste and treated jointly by the city's compact wastewater treatment facility **(El-Sonbati *et al*., 2012)**.

2. Sampling procedures

Five stations (Table 1& Fig. 1) in each drain were selected to collect samples of water, sediment, and plants during the summer of 2022. Stations were selected depending on the degree of contamination and the occurrence of the studied species. Sediment, water, and plant samples were collected from the same stations at the same time. Each station was at least five kilometres away from the neighboring station in each drain. At each station, a composite sample of sediment (n = 3) at a profile of 0– 30cm was collected. Individual samples of five perennial plant species (that were naturally growing) were sampled from each drain.

Table 1. Latitudes and longitudes of sampling stations

Drain	Station No.	Latitude	Longitude
Kitchener	1	31° 34.321′	31° 10.832′
	2	31° 32.919′	31° 10.127′
	3	31° 31.243′	31° 09.392′
	4	31° 29.853′	31° 08.842′
	5	31° 34.877′	31° 11.183′
New Damietta	6	31° 25.285′	31° 40.088′
	7	31° 27.009′	31° 43.028′
	8	31° 27.148′	31° 43.236′
	9	31° 27.666′	31° 43.043′
	10	31° 28.271′	31° 42.818′

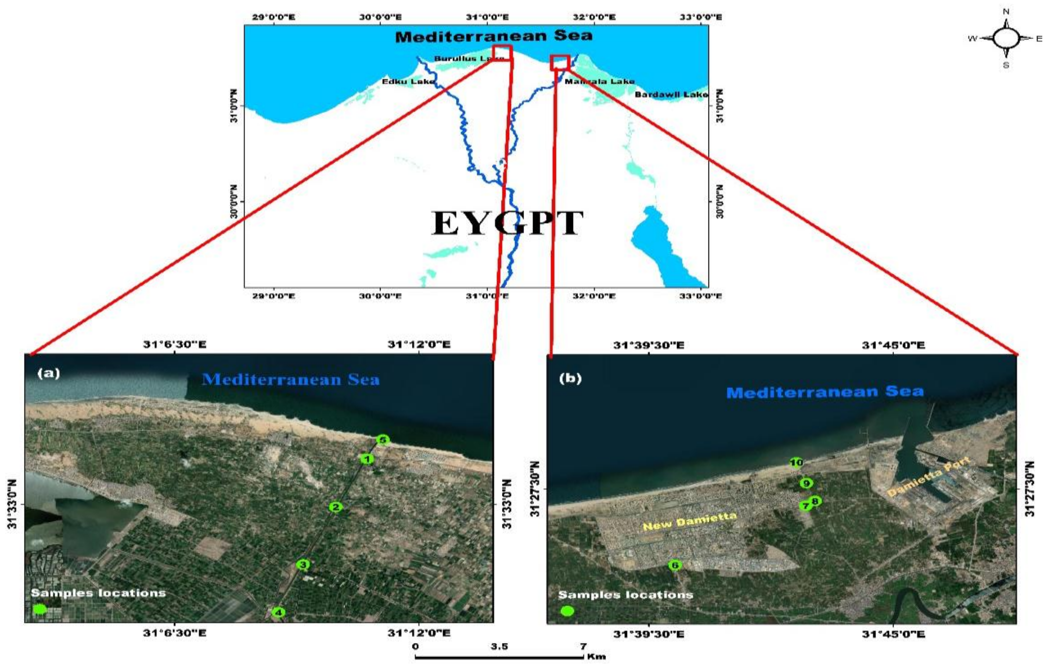

Fig. 1. A map of the Nile Delta of Egypt showing the locations of the sampling stations in **(a)** Kitchener and **(b)** New Damietta drains

2.1. Sampling of water

Samples of water were taken from stations throughout both drains. Two liters of water for each sample were taken from 20cm beneath the water's surface by plunging the plastic bottle that had been acid-washed into the water. For the purpose of determining the presence of heavy metals, water samples were collected and taken to the laboratory.

2.2. Sampling of sediment

Using a Van-Veen grab covered in polyethylene, surface sediment samples were taken **(Amini Ranjbar, 1998)**. The samples were transferred to the lab in plastic bags, air-dried at room temperature, and subsequently kept in plastic bags for further examination.

2.3. Sampling of plant

Five healthy and mature individuals of *Typha domingensis*, *Phragmites australis*, and *Eichhornia crassipes* with well-developed aboveground and belowground components were gathered from both drains (Kitchener and New Damietta). Roots and rhizomes were rinsed in the drain water to remove particles; aboveground parts were harvested, then placed in plastic bags, and taken to the lab for further analysis.

3. Sample analyses

3.1. Water analysis

Heavy metals in water samples were measured by the **APHA (2017)** method. Each 750ml filtered sample was placed into a separate funnel, and its pH was adjusted using strong nitric acid to a range of 4.8–5.2. 15 ml of 1% ammonium pyrrolydine dithiocarbamate (APDC) and 30ml of methyl isobutyl ketone (MIBK) were added to each sample. On an automatic shaker, the funnels were shaken for 15 minutes. The aqueous layer was removed after the phases were separated and placed in a spotless separating funnel, and an additional 30ml of MIBK was poured. The upper MIBK layer with the recovered metals was kept in the appropriate tiny 100ml separating funnel. For another 15 minutes, and then for another 30 minutes, the identical process was performed twice more. The MIBK extract was transferred to the 100-ml separating funnel along with at least 15 ml of 2N HNO_3, shacked, and allowed to phase separate. The 15-ml aqueous layer of 2N HNO_3 containing the chelated metal from the 750-ml sample solution was stored in tight-stopper-sealed vials until analysis. Using a Perkin Elmer Analyst 100 Atomic Absorption Spectrophotometer, heavy metals (Fe, Cu, Cd, and Pb) were measured, and the results were represented as µg/l.

3.2. Sediment analysis

To form a homogeneous mass, air-dried sediment samples were pounded into a powder using a mortar and pestle, and then sieved **(Hossain *et al*., 2020)**. The standard method was employed for digesting two grams of every powder sediment sample **(APHA, 2005)**. Two grams from every sediment sample was placed in a 50ml crucible before 10ml of pure HNO_3 was added. In order to allow for oxidation, the mixture was placed on a hot plate for 30 to 45 minutes. 2.5ml of concentrated (70%) $HClO_4$ acid was added when the mixture was cooled, and the mixture was subsequently reheated on a hot plate until the digest went clear and was beginning to dry. The samples were then filtered through Whatman number 42 filter paper after cooling **(Rahman *et al*., 2014)**. Using a Perkin Elmer Analyst 100 Atomic Absorption Spectrophotometer, heavy metals (Fe, Cu, Cd, and Pb) were determined, and the obtained values were represented as µg/g. Accuracy and precision were checked by using reference material (SD-M-2/IM).

3.3. Plant analysis

To determine the various bioaccumulation capacities, plant samples were first separated into two parts: part A contains aerial parts that are aboveground, and part B includes belowground components. Using stainless steel scissors, plant organs were cut off and stored at 2°C for examination. After being properly cleaned with distilled water, the sampled plants were separated as previously described, dried in the air, and then dried for a further 24 hours at 80°C in an electric oven. 0.5 grams each of aboveground and belowground parts were crushed and digested using a concentrated H_2SO_4/HNO_3 acid mixture **(Ullah *et al*., 2022)**. Using a flame Atomic Absorption Spectrophotometer (AAS, GBC-932), the examined heavy metals (Fe, Cu, Cd, and Pb) were measured, and findings were represented as µg/g. For maximum accuracy, samples were measured against an acid blank, and three replicates of each measurement were applied with differences less than 3%.

4. Risk assessment of heavy metals in water

The metal contamination is assessed using two different quality indexes.

4.1. Pollution index (PI)

The PI index is used to assess water for drinking, irrigation, and aquatic life suitability. It is based on calculations for each individual metal and is divided into six categories (Table 2) using the formula shown below **(Caerio *et al*., 2005)**:

$$\mathbf{PI}=\frac{\sqrt{\left[\left(\frac{c_i}{s_i}\right)^2_{max}+\left(\frac{c_i}{s_i}\right)^2_{min}\right]}}{2}$$

Where, S_i is the level of metal in accordance with national water quality standards, and C_i is the concentration of each element.

The water quality standards used in this study were the WHO's permissible limits of cadmium and iron and the USEPA's permissible limits of lead and copper, as reported in the study of **Mohod and Dhote (2013)**.

4.2. Metal index (MI)

A method of rating known as the metal index (MI) shows how individual parameters collectively affect the overall quality of water **(Tamasi & Cini, 2004)**. It is based on a comprehensive trend analysis of the existing state of affairs. The water quality is negatively correlated with the content of metal compared to its respective MAC value. The metal index, which has a value between 0 and 1, indicates how much importance is assigned to individual metal quality issues. A threshold of caution exists when the MI value exceeds 1 **(Bakan *et al*., 2010)**. MI is widely employed as a drinking water quality indicator **(Amadi *et al*., 2010)**; it is also employed to evaluate the quality of rivers **(Amadi, 2012)**. In addition, MI is used to assess the quality of seawater **(Filatov *et al*., 2005)**. **Tamasi and Cini (2004)** stated that a calculation as follows is used to determine the MI:

$$\mathbf{MI}=\sum_{i=1}^{n}\frac{C_i}{(MAC)_i}$$

Where, C_i denotes the concentration of each element, MAC denotes the maximum permitted concentration.

5. Risk assessment of heavy metals in sediment

The level of metal contamination in the two drains, and whether metal toxicity and the associated health risks threaten the quality of life and the ecosystem in this area were assessed using several pollution indices.

5.1. Enrichment factor (EF)

In the current research, the enrichment factor was used to determine whether probable trace elements in sediment came from anthropogenic or natural sources. To discriminate between natural and man-made components, iron was used as a conservative tracer. The EF is calculated as follows:

$$\textbf{Enrichment factor} = (M_S / Fe_S) / (M_b / Fe_b)$$

According to **Antoniadis *et al*. (2017)**, Fe_s is the aqua regia-extracted Fe concentration in the polluted sediment, and Fe_b is the background reference Fe content in uncontaminated areas. Table (2) lists the EF values according to their classification.

5.2. Contamination factor (CF)

The ratio of the measured concentration of heavy metals in the sediment of the water body to the pre-industrial reference value for the same metal yields the contamination factor **(Häkanson, 1980)**. The total number of contamination factors is used to define the contamination level. The following equation can be used to calculate the CF, which is the ratio created by dividing each metal's concentration in sediments by the baseline or background value:

$$\mathbf{CF = C_s / C_{Ref}}$$

The background value is based on element abundances in sedimentary rocks (shale) and corresponds to the baseline concentrations reported by **Turekian and Wedepohl (1961)**. Table (2) presents the categorization of CF levels.

5.3. Degree of contamination (DC)

The degree of contamination (DC), which is the total of all contamination factors for a certain site, is another index that may be obtained from the CF values **(Hökanson, 1980)**:

$$\mathbf{DC = \sum_{i=1}^{N} CF_i}$$

Where, n is the number of elements present, and CF is the single contamination factor. The values of DC, which are less than (n), indicate a low degree of contamination; $n \leq DC < 2n$ indicates a moderate degree of contamination; $2n \leq DC < 4n$ indicates a considerable degree of contamination; and $DC > 4n$ indicates a very high degree of contamination. The terms listed below have been used to describe the level of contamination in the study area:

$DC < 7$ indicates modest levels of pollution, $7 < DC < 14$ indicates moderate levels of contamination, $14 > DC < 28$ indicates considerable levels of contamination, and $DC > 28$ indicates extremely high levels of contamination. Where the number of examined heavy metals, n, is equal to 4.

5.4. Pollution load index (PLI)

The PLI suggested by **Tomlinson *et al*. (1980)** gives the local population with some understanding of the amount of a component in the environment. A single site's PLI is equal to the root of the number (n) of multiplied together contamination factor (CF) values.

$$\mathbf{PLI = (CF_1 \times CF_2 \times CF_3 \times \ldots\ldots \times CF_n)^{1/n}}$$

Where, n denotes the number of metals (four in the current study), and CF denotes the contamination factor. According to **Tomlinson *et al*. (1980)**, a PLI value of zero denotes perfection, a value of one shows the presence of just baseline levels of pollutants, and values above one would signify a continual deterioration in the site's quality. PLI values greater than 1 indicate pollution, while PLI values less than 1 show no pollution **(Seshan *et al*., 2010)**.

5.5. The Geo-accumulation index (I_{geo})

The metal pollution in the soils and aquatic sediments is measured using this index. The following equation **(Muller, 1969)** was utilized to compute the geo-accumulation index (I_{geo}) for sediment samples:

$$\mathbf{I_{geo} = Log_2 (C_n/1.5B_n)}$$

Where, B_n is the geochemical background value for element n in average shale; C_n is the measured concentration of heavy metals in sediments, and 1.5 is the background matrix correction. **Buccolieri *et al*. (2006)** divided the geo-accumulation index (I_{geo}) into seven divisions (Table 2).

5.6. Potential ecological risk index (RI)

The assessment of the potential ecological risk of heavy metal contamination was suggested as a diagnostic tool for reasons of water pollution control due to the rising concentration of heavy metals in sediments and their subsequent release into the water, which might threaten ecological health **(Hu *et al*., 2019)**. The potential ecological risk index (RI), which is computed as the total of all risk factors (E^i_r) for heavy metals in sediments, was used to measure the level of heavy metal pollution in sediments in accordance with the toxicity of heavy metals and the response of the environment. **(Hakanson 1980; 1988)**:

$$\mathbf{RI = \sum_{i=1}^{n} E^i_r}$$

$$\mathbf{E^i_r = T^i_r / C_f}$$

Where, C_f stands for the contamination factor for the element "i", and T^i_r indicates the toxic response factor for the given element “i”, which takes into account both the sensitivity and toxic requirements. Table (2) displays the pollution levels based on RI and E^i_r.

6. Phytoremediation potentials of the selected aquatic plants

The bioaccumulation factor (BAF) and the translocation factor (TF) were used to evaluate the ability of the selected macrophytes' above- and belowground components to accumulate heavy metals.

6.1. Bio-accumulation factor (BAF)

For heavy metals, the bioaccumulation factor (BAF) was determined. BAF describes a plant species' capacity to efficiently uptake and accumulate a certain element in its tissues from the surrounding medium (sediment or water). As emergent reeds, *Typha domingensis, Phragmites australis,* and free-floating *Eichhornia crassipes*, the following biological concentration factors were calculated using dry weight (mg/kg) data **(Nguyen *et al*., 2005)**:

$$\mathbf{BAF = C_{root}/C_{sediment}} \text{ (for } \textit{T. domingensis} \text{ and } \textit{P. australis}\text{)}$$

$$\mathbf{BAF = C_{root}/C_{water}} \text{ (for } \textit{E. crassipes}\text{)}$$

Where, $C_{\text{sediment (or) water}}$ and C_{root} are the respective concentrations (mg kg^{-1}DW) of a particular element in the study species' sediment or water, and roots **(Eid *et al*., 2019)**. Higher BAF results indicate a better capacity for bioaccumulation **(EPA, 2007)**.

6.2. The translocation factor (TF)

In order to measure a plant's ability to move heavy metals from the root system to the shoot system, the translocation factor (TF) was computed as follows **(Ghosh & Singh, 2005)**:

$$\mathbf{TF = C_{shoot} / C_{root}}$$

Where, C_{shoot} and C_{root} represent the concentration of the same heavy metals in the shoot and root systems, respectively, in mg kg^{-1}.

Table 2. The standards utilized in the study for the various ecological risk assessment indices

Index	Category	Degree	Reference
EF	EF < 1	No enrichment	**(Chen *et al*., 2007; Sakan *et al*., 2009)**
	1 < EF < 3	Minor enrichment	
	3 < EF < 5	Moderate enrichment	
	5 < EF < 10	Moderately severe enrichment	
	10 < EF < 25	Severe enrichment	
	25 < FE < 50	Highly severe enrichment	
	EF > 50	extremely severe	
CF	CF < 1	Low contamination factor	**(Hakanson, 1980)**
	1 ≤ CF < 3	Moderate contamination factor	
	3 ≤ CF < 6	Considerable contamination factor	
	CF ≥ 6	Very high contamination factor	
I_{geo}	$Ig_{eo} \leq 0$	Uncontaminated	**(Muller, 1981)**
	$0 < I_{geo} \leq 1$	Uncontaminated to moderately contaminated	
	$1 < I_{geo} \leq 2$	Moderately contaminated	
	$2 < I_{geo} \leq 3$	Moderately to heavily contaminated	
	$3 < I_{geo} \leq 4$	Heavily contaminated	
	$4 < I_{geo} \leq 5$	Heavily to extremely contaminated	
	$I_{geo} > 5$	Extremely contaminated	
RI	ER < 150	Low grade	**(Håkanson, 1980)**
	150≤ ER < 300	Moderate	
	300 ≤ ER< 600	Severe	
	ER > 600	Serious	
E^i_r	$E^i_r < 40$	Low	**(Håkanson, 1980)**
	$40 \leq E^i_r < 80$	Moderate	
	$80 \leq E^i_r < 160$	Considerable	
	$160 \leq E^i_r < 320$	High	
	$E^i_r > 320$	Serious	
PI	< 1	No effect	**(Goher *et al*., 2014)**
	1 – 2	Slightly affected	
	2 – 3	Moderately affected	
	3 – 5	Strongly affected	
	> 5	Seriously affected	

7. Statistical analysis

Before conducting one-way and two-way ANOVAs, the data were checked for normality and equality of variances. Moreover, the t-test was considered in the cases of homogeneity and normality. Where the samples weren't homogeneous, the data was either converted using logarithms or square roots, or multiple comparisons were made using non-parametric tests (Kruskaul-Wallis H and Mann-Whitney U) **(Zar, 1996; Dytham, 2003)**. The Pearson's r coefficient was used to examine any linear correlation between plant tissues, water, and sediment. Statistical Software Package SPSS version 16.0 was used for all statistical calculations (SPSS Inc., Chicago, U.S.A.).

RESULTS AND DISCUSSION

1. Heavy metals in water

According to the current investigation, there was no significant variance ($P > 0.05$) in the amounts of Fe, Cu, Cd, and Pb in the two drains (Table 3). The results presented a wide range of heavy metal concentrations, with Fe having the highest amount (208.4, 190.64 µg/l) in the New Damietta and the Kitchener Drains, respectively, while Cd showed the lowest level (0.56, 0.16 µg/l) in the New Damietta and the Kitchener Drains, respectively. The Pb recorded a mean concentration (5.69, 16.33 µg/l) and the Cu was recorded (2.17, 2.84 µg/l) in the New Damietta and the Kitchener Drains, respectively. According to the research outcomes, water contamination is directly proportional to the degree of environmental contamination **(Vaishnavi & Gupta, 2015)**. The Kitchener and New Damietta Drains are susceptible to receiving considerable volumes of surface run-off from farmlands as well as effluents from nearby human settlements that discharge variable degrees of wastewater. Rapid agricultural development, non-point source run-off carrying fertilizers and pesticides, increased industrial activity, increased atmospheric deposition, and municipal wastewater treatment plants were all shown to be the main causes of heavy metal pollution in drains **(Khaki *et al*., 2011)**. Based on the limits of the **US EPA (2002)** and the World Health Organisation (WHO, 2011), the findings demonstrated that neither of the two drains had heavy metal contamination and reflected minor impacts of human activities except for Pb in station (5), "Kitchener drain outlet (sea)," which was 64.7 µg/l and station (6) at New Damietta Drain, which was higher than the limits of **WHO (2011)** (13.52 µg/l). Many studies have determined that human activity, including the use of pesticides, fertilizers, sewage sludge, automobile exhausts, and car batteries, is the primary source of lead (Pb) **(Zhang *et al*., 2019)**. This result agrees with those of **Beheary *et al*. (2018)** and **Eid *et al*. (2020)**.

Table 3. Heavy metal concentrations (µg/l) in the water of two drains (Kitchener and New Damietta) during 2022

Drain	Station No.	Cu	Pb	Fe	Cd
Kitchener	1	2.76	4.12	19.26	1.72
	2	2.08	3.82	29.28	2.00
	3	1.94	4.94	13.76	0.48
	4	3.66	4.06	36.24	1.34
	5	3.74	64.70	190.64	0.16
	Mean	2.84	16.33	57.84	1.14
	±SD	0.85	27.04	74.75	0.79
New Damietta	6	2.22	13.52	51.54	1.22
	7	2.04	2.06	52.92	0.88
	8	2.48	2.76	57.24	0.58
	9	1.76	5.08	97.10	0.64
	10	2.36	5.02	208.4	0.56
	Mean	2.17	5.69	93.44	0.78
	±SD	0.28	4.58	66.96	0.28
***P*- value**		0.15	0.41	0.45	0.69
Permissible limits					
US EPA (2002)		50	50	300	2.37
WHO (2011)		2000	10	300	3

2. Risk assessment of heavy metals in water

The pollution and metal indices of the heavy metals obtained in this investigation are shown in Table (4). The findings of this investigation revealed that the metal pollution index (PI) of Cu, Fe, and Cd was less than one, according to the classification of metal pollution index (PI) for water **(Goher *et al.*, 2014)**, which indicates that they have no effect on the water quality, except for Pb of the Kitchener Drain (PI = 2.16), which has a moderate effect on the water quality considering human and aquatic health. The metal index (MI) also showed that Pb in the two drains, Fe in the New Damietta Drain, and Cd in the Kitchener Drain are at the threshold level (MI > 1), while Cu in the two drains, Fe in the Kitchener Drain, and Cd in the New Damietta Drain pose no threat (MI < 1). This shows that heavy metal contamination is endangering the water quality of the drains, which could have negative repercussions for aquatic health. According to **Ibrahim and Omar (2013)**, fluctuations in the quantity of agricultural drainage water, sewage effluents, and industrial wastes released into waterways are the main reasons for the variation in the concentration of heavy metals in water. In addition, water quality can be impacted when the rate of atmospheric deposition, storm water runoff, residential discharges, or wastewater from factories exceeds the carrying capacity of water **(USEPA, 1998)**.

Table 4. Pollution index (PI) and metal index (MI) of the heavy metals in the Kitchener and New Damietta Drains during 2022

Drain	Heavy metal	PI	Effect of the PI for human and aquatic health	MI	Effect of the MI for human and aquatic health
Kitchener	Cu	0.001	No effect	0.007	No threat
	Pb	2.160	Moderately effect	5.440	Threshold level
	Fe	0.317	No effect	0.960	No threat
	Cd	0.201	No effect	1.140	Threshold level
New Damietta	Cu	0.001	No effect	0.005	No threat
	Pb	0.456	No effect	1.900	Threshold level
	Fe	0.360	No effect	1.560	Threshold level
	Cd	0.134	No effect	0.776	No threat

3. Heavy metals in sediment

Heavy metals occur naturally in certain concentrations in the Earth's crust. A rise in heavy metal concentrations in ecosystems as a result of human activity increases pollution and poses a danger to human health **(Esposito *et al*., 2018)**. The New Damietta Drain had more pollution than the Kitchener Drain in the current investigation; this can be due to severe sources of pollutants such as domestic sewage, agricultural drainage, and industrial effluents that discharge straight into its stream without any treatment facilities **(EEAA, 2017)**. The amount of heavy metals in sediments was ordered in the current investigation as Fe > Pb > Cu > Cd. These findings concur with those of **El-Amier *et al*. (2020)** and **Fawzy *et al*. (2012)**, who observed a comparable pattern of heavy metal distribution in several irrigation and drainage canals in Egypt.

Copper (Cu) is necessary for humans, animals, and plants in low concentrations, yet it can be damaging to biota **(El-Gharapawy, 2013)**. According to Table (5), the concentrations of Cu in sediment samples along the Kitchener drain ranged from 0.8 to 10.08µg/ g, and they ranged along the New Damietta Drain from 3.8 to 46.43µg/ g. The New Damietta Drain recorded the highest value, while the Kitchener Drain recorded the lowest value. The highest value may be related to agricultural wastewater discharge, which contains insecticides and pesticides and enters the drain; this could be an additional source of Cu **(Balbaa *et al*., 2007)**. Findings from Table (5) show that there was no significant ($P < 0.05$) variation in Cu along the sediments of the two drains under study. The current amounts of Cu in drain sediments are less than or comparable to those reported by **Mahmoud and Ghoneim (2016)**, **Aitta *et al*. (2019)** and **El-Amier *et al*. (2021)**, who stated that the copper concentration in sediment samples varied between 5.16 and 386µg/g. The mean value of Cu concentrations in the two drains is less than what the **EPA (2002)** established as internationally acceptable.

Lead (Pb) is classified as potentially dangerous to most forms of life by the United States Environmental Protection Agency (US-EPA) due to its high persistence and a variety of previous and contemporary usages **(Chen *et al*., 2006)**. In the present study, Pb concentrations ranged from 14.06 to 22.84µg/ g with a mean value of 17.02 µg/g in the New Damietta Drain, while they ranged from 6.8 to 12.49 µg/g with a mean value of 9.25 µg/g in the Kitchener Drain. The New Damietta Drain had the greatest Pb concentration, which was likely caused by Pb being incorporated into agricultural soil as a result of numerous sources of contamination **(Alloway, 1995)**. The mean Pb concentrations varied significantly ($P< 0.05$) across the two drains (Table 5). According to **EPA (2002)**, the mean value of Pb exceeds the permissible limits (10 µg/g). These findings concur with those of **El-Amier *et al*. (2018)**, **Abdelaal *et al*. (2021)** and **El-Metwally *et al*. (2021)**.

As shown in Table (5), iron (Fe) is the most plentiful element in the two drains. The highest concentrations were 143.25 and 142.75µg/ g in the New Damietta and the Kitchener Drains, respectively. Large amounts of Fe in sediment may be attributed to anthropogenic activities such as sewage runoff, fertilisers, and iron sulphate used in fertilizer and herbicide manufacturing **(Khan *et al*., 2017)**. Results in Table (5) reveal that there was no significant difference ($P> 0.05$) between the mean values of Fe concentrations in the two drains. According to **Mahmoud and Ghoneim (2016)**, **Aitta *et al*. (2019)**, **El-Amier *et al*. (2021)**, and **El-Metwally *et al*. (2021)**, the range of Fe concentration in sediment samples was 659.20 to 4629.23 µg/g. The Fe levels in the current study were lower than those reported by these groups. The Fe concentrations were below limits (15000 µg/g) as reported by the **US-EPA (2002)**.

Cadmium (Cd) is found in trace amounts in phosphatic fertilizers. Cd pollution is caused by atmospheric deposition **(ATSDR, 2008)**. Even at low concentrations, Cd is harmful to aquatic life. When it is present in high concentrations in sediment, the absorption through food will increase. Our finding showed that Cd concentrations ranged between 1.91 and 5.91 with a mean value 3.38µg/g in the Kitchener Drain, and it ranged between 0.4 and 3.13 with a mean value 1.22µg/g in the New Damietta Drain. The numerous chemicals used in farming operations, such as pesticides and phosphate fertilizers, are responsible for the greater amounts of Cd in the Kitchener Drain compared to the New Damietta Drain **(Yahya *et al*., 2018)**. It is evident from Table (5) that there was a significant ($P<0.05$) difference in the mean Cd concentrations across the two drains. The levels of Cd in the sediments of the current research sites were less than the international allowed standard (6µg/g), according to **US-EPA (2002)** data. This finding coincides with those of **Beheary *et al*. (2018)** and **El-Metwally *et al*. (2021)** and disagrees with the results of **El-Alfy *et al*. (2017)** who stated that the mean value of Cd exceeded the standard limits.

Table 5. Heavy metal concentrations and the Mean ±SD values of heavy metals in sediments of two drains (Kitchener and New Damietta) during 2022

Drain	Station No.	Cu	Pb	Fe	Cd
Kitchener	1	1.275	10.940	135.250	3.430
	2	5.063	8.013	139.000	3.480
	3	10.075	12.490	142.750	5.913
	4	1.225	6.800	138.000	1.913
	5	0.800	8.025	135.500	2.163
	Mean	3.690	9.250	138.100	3.380
	±SD	3.970	2.360	3.050	1.590
New Damietta	6	4.300	14.063	139.250	3.125
	7	3.800	15.300	141.500	0.138
	8	46.425	17.400	142.630	0.700
	9	9.050	22.838	143.250	1.738
	10	2.588	15.513	140.500	0.400
	Mean	13.230	17.020	141.430	1.220
	±SD	18.720	3.460	1.610	1.230
P- value		0.297	0.003	0.063	0.043
Permissible limits worldwide					
US-EPA		25	10	15000	6

4. Risk assessment of heavy metals in sediment

Sediment contamination analysis is regarded as crucial for evaluating the health of ecosystems; however, element concentration analysis alone is insufficient to identify probable anthropogenic and wellness consequences. Thus, a number of quantitative indices have been developed to assess the level of environmental contamination and ecological harm that heavy metals present **(El Zrelli *et al*., 2015)**. To distinguish between anthropogenic and natural sources of elements, the enrichment factor (EF) is a suitable index **(Huu *et al*., 2010)**. In accordance with this, EF values lower than 1.5 indicate an element's natural origin, but EF values greater than 1.5 indicate an element's anthropogenic origin **(Alahabadi & Malvandi, 2018)**. Based on the EF results, Cu, Pb, and Cd had mean values of the index that were greater than 1.5 at every station in the two drains (Fig. 2), proving that these elements came mainly from anthropogenic sources. The enrichment factor value of Cu was 6.89-82.4 (moderate enrichment to extremely severe enrichment); Pb was 115.06-204.26 (extremely severe enrichment), and Cd was 2157.34-6447.49 (extremely severe enrichment) in the sediment samples of the Kitchener Drain, revealing a significant agricultural influence that may compromise the quality of the sediments in the Mediterranean Sea. The enrichment factor value of Cu was 21.5–380.03 (severe enrichment–extremely severe enrichment), Pb was 235.81–372.26 (extremely severe enrichment), and Cd was 151.27–3493.42 (extremely severe enrichment) in the sediment samples of the New Damietta Drain, which comes mainly from operations like industrial waste deposition and discharge from farming regions. The computed EF values obtained in the subsequent successions were: Cd > Pb > Cu in both drains. From the results, we found that the concentration of Cu and Pb in the New Damietta Drain is higher than that of the Kitchener Drain although Cd is higher in the Kitchener Drain than the New Damietta Drain. Accordingly, copper (Cu) had the lowest appearance although cadmium (Cd) is more common than other metals. Results revealed that phosphatic fertilizers and untreated wastewater from industrial and agricultural drains were the sources of the most enriched and abundant anthropogenic element in the study locations, which was Cd. Additionally, the use of pesticides is another significant contributing factor to the Cd contamination of sediment. This outcome is almost entirely consistent with the findings of **El-Alfy *et al*. (2017)** who noticed that, Cd was the most common and enriched element in the Kitchener Drain, and **Beheary *et al*. (2018)**, who claimed that EF values were found in the following sequences: Cd > Pb> Cu in the New Damietta Drain.

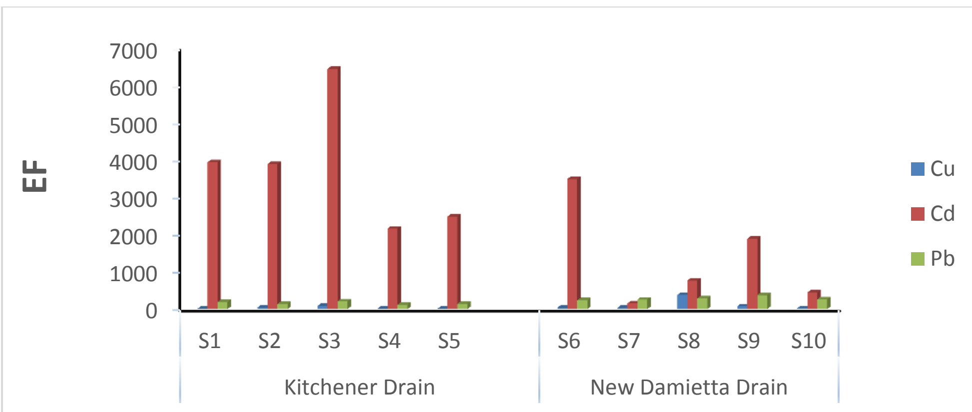

Fig. 2. Enrichment factors (EF) in sediment of both drains

Based on the data displayed in Fig. (3), the contamination factor (CF) of Fe, Cu, and Pb of all stations of the Kitchener Drain were less than 1, showing low contamination. On the other hand, in the New Damietta Drain, the contamination factor (CF) of Cu showed low contamination, except in station 8, which showed moderate contamination; Pb showed low contamination, except in station 9, which showed moderate contamination, and Fe in all stations was less than 1, showing low contamination. All stations of the Kitchener Drain had very high CF levels for Cd, while in the New Damietta Drain, the concentration of Cd was less than that of the Kitchener Drain, ranging from low to considerable contamination, except station 6, which showed very high contamination. The computed CF values occurred in the following sequences: Cd > Pb > Cu > Fe for all stations under study. It was noticed that, Fe is the least likely metal to affect the pollution load; however, Cd is the main pollutant to generate significant pollution. These findings concur with those of **El-Alfy *et al*. (2017)** who noticed that, Fe showed low CF and Cd showed very high CF levels in the Kitchener Drain, and **Beheary *et al*. (2018)** who noted that, Fe, Cu, and Pb displayed low contamination, while Cd displayed moderate contamination in the New Damietta Drain. In every sample in the coastal zone from Damietta to Port Said, the Fe, Cu, and Pb contamination factors were low, according to the research of **Abd El-Hamid *et al*. (2016)**.

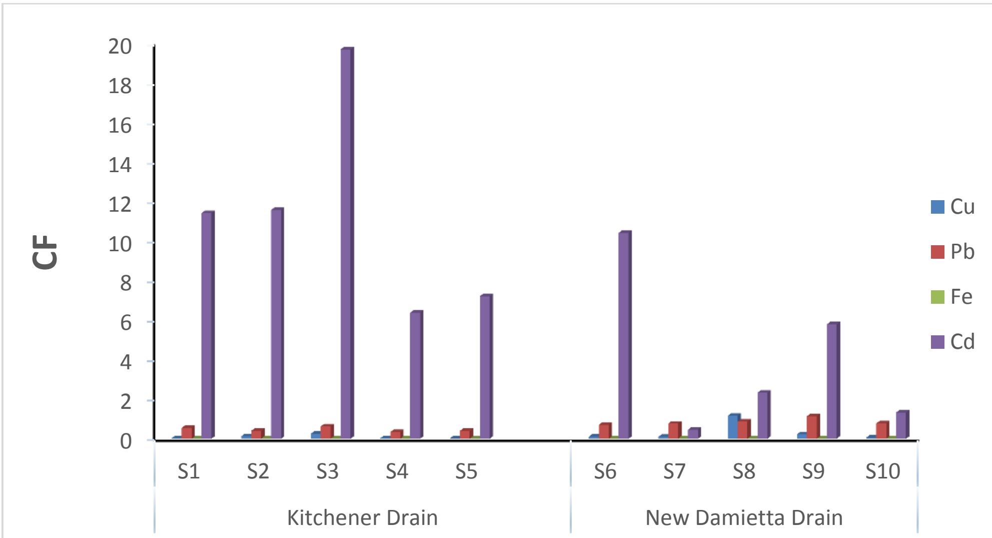

Fig. 3. Contamination factor (CF) in sediment of both drains

The pollution load index (PLI) is another index used to measure the degree of contamination of various elements in sediments. Fig. (4) displays the obtained PLI values, and they were less than 1 in both drains, so there was no appreciable contamination. The decline in PLI values shows that metal content is diluted and dispersed with increasing distance from source sites. PLI can indicate the trend spatially and temporarily. In addition, it provides valuable information and advice to policymakers and decision-makers on the pollution level of the area **(Harikumar & Jisha, 2010)**. On the other hand, the degree of contamination (DC) values (Fig. 5) ranged from moderate to high contamination in the Kitchener Drain and from low to considerable contamination in the New Damietta Drain. This is attributable to toxins being transported from farmland, sewage systems, and tributaries before being dumped into the drainage stream. The current findings concur with those from studies on 10 stations throughout the central zone of the Egyptian Mediterranean coast conducted by **El-Baz and Khalil (2018)**.

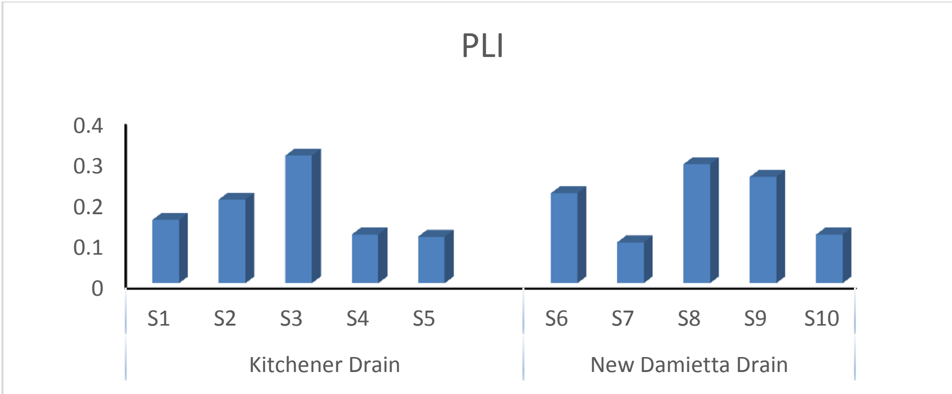

Fig. 4. Pollution load index (PLI) in sediment of both drains

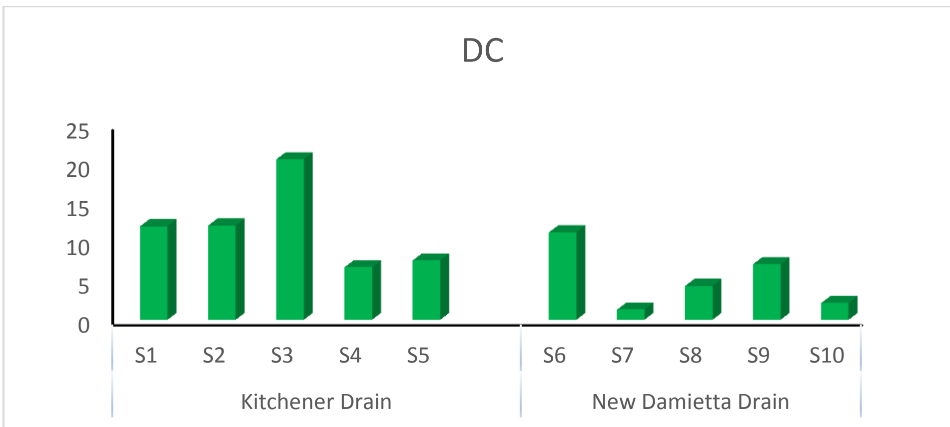

Fig. 5. Degree of contamination (DC) in sediment of both drains

The potential ecological risk index (RI) was used to describe the E^i_r of single heavy metals in sediments. The RI was used to assess the ecological sensitivity of heavy metal pollution in the sediments in accordance with the toxicity of the heavy metals and the responses of the environment **(Håkanson, 1980)**. Table (6) provides a summary of the findings from the assessment of the potential ecological risk factor E^i_r and the potential ecological risk index (RI). The E^i_r of heavy metals in the sediments of the drains can be ranked as follows: Cd > Pb > Cu. The values of the E^i_r for Pb and Cu were less than 40 ($E^i_r < 40$; i.e., low ecological risk) in the two drains. The values of the E^i_r for Cd ranged from low ($E^i_r < 40$) to moderate ($40 \leq E^i_r < 80$) and high ($160 \leq E^i_r < 320$) in the New Damietta Drain, while they ranged from high ($160 \leq E^i_r < 320$) to serious ($E^i_r > 320$) in the Kitchener Drain. In addition, Cd is the most hazardous heavy metal, exceeding the geochemical background value seen in typical shale deposits of the element. Therefore, it is necessary to further investigate the toxicity values for cadmium in the middle Nile Delta to estimate their spread on a broader level, examine a plan for limiting these pollutants, and evaluate their potential effects. From Table (6), the values of RI ranged from moderate to severe in the Kitchener Drain, while in the New Damietta Drain, they were low except in stations 9 (moderate) and 6 (severe). Comparing the Kitchener Drain to the New Damietta Drain, we found that the potential ecological risk is higher in the Kitchener Drain. Human activities have a significant impact on these regions' environmental dangers and heavy metal concentrations.

Table 6. Ecological risk factor and potential ecological risk index in the sediment

Fig. 6. The geo-accumulation index of the heavy metals in the sediment of both drains

Drain	Station	Potential ecological risk factor E^i_r			RI	Risk grade
		Cu	Pb	Cd		
Kitchener	1	0.16	2.73	342.60	345.49	Severe
	2	0.64	2.00	347.40	350.04	Severe
	3	1.26	3.12	591.30	595.68	Severe
	4	0.16	1.70	191.40	193.26	Moderate
	5	0.10	2.01	216.30	218.41	Moderate
New Damietta	6	0.54	3.52	312.60	316.66	Severe
	7	0.48	3.83	13.80	18.10	Low
	8	5.81	4.35	69.90	80.06	Low
	9	1.13	5.71	173.70	180.54	Moderate
	10	0.33	3.88	39.90	44.11	Low

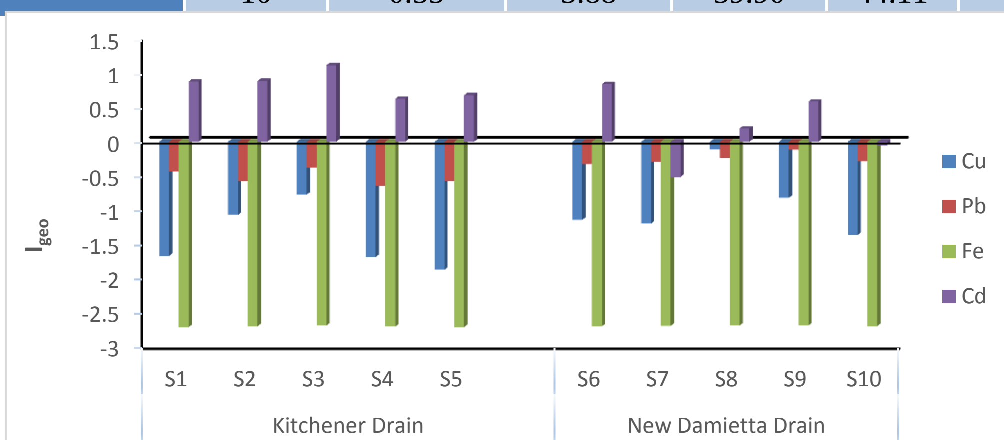

Fig. 6. The geo-accumulation index of the heavy metals in the sediment of both drains

Fig. (6) presents the I_{geo} index's findings. According to **Müller (1969)**, the majority of the elements studied (Fe, Cu, and Pb) were included in the zero class (i.e., practically uncontaminated) at all stations of the two drains. The Cd of the Kitchener Drain is class 1 ($0 < I_{geo} < 1$), showing uncontaminated to moderate contamination, with the exception of station 3, which belongs to class 2 ($1 < I_{geo} < 2$), showing moderate contamination, Although Cd in the New Damietta Drain falls in class 1 ($0 < I_{geo} < 1$), indicating uncontaminated to moderate contamination; except for stations 7 and 10, it falls in the zero class (i.e., practically uncontaminated). Therefore, according to **Müller (1969)**, in the area of the two drain streams, the metals Fe, Pb, and Cu are all uncontaminated, whereas Cd is moderately contaminated in the Kitchener Drain and uncontaminated to moderately contaminated in the New Damietta Drain, with an order of Cd > Pb > Cu > Fe.

5. Heavy metals phytoremediation

5.1. Heavy metals concentrations in plants

When compared to terrestrial plants, aquatic macrophytes are better suited, more effective and more suitable for phytoremediation of pollutants in sludge, sediment, soil, and water, especially for the treatment of residential effluents and wastewaters **(Sood *et al*., 2012)**. The results for the concentrations of heavy metals in the below ground and above ground parts of the three most common plant species (*Phragmites australis*, *Typha domingensis*, and *Eichhornia crassipes*) expanding along the investigated drains are shown in Table (7). The largest amounts of Cu, Pb, and Cd were preserved in the tissues of *E. crassipes* among the investigated species, while the highest concentrations of Fe were found in *P. australis*. The underground tissues of *E. crassipes* had the highest concentrations of Cu, Pb, and Cd (24.04, 61.61, and 16.85µg/g, respectively), while the underground tissues of *P. australis* contained the highest concentration of Fe (223.5µg/g). Meanwhile, *P. australis* aboveground tissues had the lowest concentrations of Cu and Pb (2.516 and 24.12µg/g, respectively), while *E. crassipes* and *T. domingensis* aboveground tissues had the lowest concentrations of Fe and Cd (65.94 and 7.51 µg/g, respectively). The results diverge from those that have been reported in other investigations for the same plants in equivalent Egyptian canals and drains. This could be explained by variations in the number of contaminants, the sample period, the collection and analysis procedures, and the chemical and physical characteristics of the waterway **(Eid *et al*., 2020)**. For instance, both *P. australis* and *E. crassipes* had lower Cd and Pb concentrations than those observed for the same species in the Nile Delta's Kitchener Drain in the study of **Eid *et al*. (2020)**. **El-Amier *et al*. (2018)** showed lower Pb, Fe, and Cd concentrations for *P. australis, E. crassipes,* and *T. domingensis* than the same species in the present study. All macrophytes in the current investigation showed Cu concentrations that were lower than the maximum threshold suggested by **WHO (2011)**. The mean Pb, Fe, and Cd concentration values recorded for the examined species tissues in the current experiment were within the phytotoxic limits (30–300, > 500, and 5–30, respectively), with respect to the normally safe and phytotoxic levels of heavy metals **(Kabata-Pendias, 2011)**. The results are in harmony with previous studies of **El-Amier *et al*. (2018)** and **Wang *et al*. (2005)**, indicating elevated levels of heavy metals in reeds (*P. australis* and *T. domingensis*) and free-floating macrophytes (*E. crassipes*).

According to **Shen *et al.* (2021)**, structure, conveyance by water, and species of the plant all affect how heavy metals are distributed in various plant tissues, with the root acting as the main entry point for heavy metals. The heavy metal concentrations in this study took place in the following order for the above- and below-ground tissues of the three macrophytes: Fe > Pb > Cd > Cu (Table 7). In this context, heavy metal concentrations in the root tissue of the analyzed macrophytes are higher than in the shoot system. This is consistent with other studies that found roots exhibited a greater potential for accumulation than shoots **(Cicero-Fernández *et al*., 2016; Saha *et al*., 2017; El-Amier *et al*., 2020)**. Heavy metals' complexation with sulfhydryl groups, which reduces heavy metals' translocation to the shoot system, may be the cause of the high accumulation of heavy metals in roots **(Singh *et al*., 2004)**. In addition, the fact that the roots are the first organ exposed to heavy metals may help explain why there are higher concentrations of heavy metals in the root system than in the shoot system. Furthermore, there have been numerous studies on the synthesis of phytochelatins, which can sequester heavy metals; as a result, increased accumulation occurred in the root system **(Eid & Shaltout, 2014)**. It is evident that the New Damietta Drain has higher levels of heavy metals in the examined macrophytes than the Kitchener Drain.

Table 7. Mean concentration values of heavy metals in the three macrophytes

Drain	Metal	*P. australis* (μg/g)		*T. domingensis* (μg/g)		*E. crassipes* (μg/g)	
		above	below	above	below	above	below
Kitchener	Cu	2.52	8.16	3.66	7.37	2.86	2.92
	Pb	42.12	51.64	54.28	37.11	52.23	61.61
	Fe	116.68	216.13	77.67	206.40	152.92	220.35
	Cd	10.30	14.65	12.42	8.67	12.62	16.86
New Damietta	Cu	3.24	11.38	2.63	8.97	2.84	24.06
	Pb	43.86	48.10	53.78	60.88	59.14	57.52
	Fe	147.83	223.50	121.87	223.20	65.94	185.28
	Cd	11.91	11.97	7.51	14.51	10.72	10.78

According to the ANOVA analysis (Table 8), plant Cu concentration showed a highly significant variation ($P< 0.001$) with plant tissues, and Pb levels of the studied plants varied significantly ($P< 0.05$) with plant species. Concerning the plant tissues, a highly significant difference ($P< 0.001$) was detected in plant iron concentration. Nonetheless, the interaction of the other variables exerts insignificant variation on plant Fe concentration. Besides, the results in Table (8) reveal that the levels of Cd showed a significant variation ($P< 0.05$) with plant tissues. The results implied that Cd might accumulate in all plant tissues (shoots and roots). On the other hand, fluctuations in stations and the interaction of the other variables showed an insignificant variation in the Cd levels in the plant.

Table 8. F- values of variation of heavy metals concentrations in the studied plants in relation to variation in stations, tissues and species

Variables	Cu	Pb	Fe	Cd
Stations	1.898 ns	0.945 ns	0.405 ns	0.717 ns
Tissues	**13.387*****	1.559 ns	**33.074*****	**4.338***
Species	1.615 ns	**3.696***	0.285 ns	1.609 ns
Stations × Tissues	1.870 ns	1.552 ns	0.967 ns	0.633 ns
Stations × Species	0.492 ns	0.492 ns	0.247 ns	0.590 ns
Tissues × Species	0.206 ns	1.188 ns	0.730 ns	0.133 ns

The significant values are in the bold letters. *P <0.05; **P < 0.01; ***P< 0.001, and ns: not significant (P> 0.05).

5.2. Correlation coefficient between heavy metals in water, sediment & plants

Table (9) provides an overview of the interactions between heavy metals in the water, sediment, and plants in the study regions. An analysis of heavy metals revealed significant positive correlations between *Eichhornia crassipes* and water (P< 0.05), including Pb-Fe (r= 0.938). The positive correlation here supports a translocation or deposition process, as well as similar origins for these metals, whether natural or manufactured. On the other hand, there is a significant negative correlation (P< 0.05) between *Eichhornia crassipes* and water, including Pb-Cd (r= -0.930). This negative correlation might support the antagonistic relations hypothesis. The co-assimilation of lead and cadmium at the same phase is probably the cause of the highly significant correlation between lead and cadmium in aquatic plants **(El-Sarraf, 1995)**. The results are consistent with those of previous studies **(Fawzy *et al*., 2012; Eid *et al*., 2020; Abdelaal *et al*., 2021)**. A significant correlation of heavy metal concentration between water and the macrophytes specifies that the macrophytes reflect the long-term effects of damaging the environment, a result which agees with several authors who have shown that aquatic macrophytes record temporal changes in heavy metals **(Vardanyan & Ingole, 2006)**.

A significant positive correlation (P< 0.05) was observed in *P. australis* and sediment between Cu and Fe (r = 0.673). According to **Alloway and Davis (1971)** and **El-Sarraf (1995)**, the biological mechanisms involved in assimilation in macrophytes were thought to be the reason of the positive correlation for Cu and Fe. In light of the results, no significant correlations were found between *T. domingensis* and sediment for all the heavy metals.

We can learn about heavy metal sources and processes by using correlation metrics **(Manta *et al*., 2002)**. It is clear that the variable metal concentrations and the area's various sediment characteristics, as well as differences in the absorption of plants can be responsible for the weak correlation between heavy metals in sediment and plants **(Naz *et al*., 2013)**.

Table (10) summarizes the correlations among heavy metal concentrations (µg/g dw) in plants in the two drains. The results indicated that there is no significant correlation except for Cd-Fe, which has a significant positive correlation (r= 0.481; *P*< 0.05). This indicates that cadmium and iron have a similar origin, whether natural or synthetic.

Table 9. Pearson correlation coefficient (r- values) between heavy metals concentrations of water, sediment, and plant species/tissues in the Kitchener and the New Damietta Drains

Species	Water				
Eichhornia crassipes	**Metals**	**Cu**	**Pb**	**Fe**	**Cd**
	Cu	-0.320	0-.330	-0.188	-0.315
	Pb	0.690	0.861	**0.938***	**-0.930***
	Fe	0.121	-0.188	-0.384	0.728
	Cd	0.638	0.496	0.321	0.109
Phragmites australis	**Sediments**				
	Metals	**Cu**	**Pb**	**Fe**	**Cd**
	Cu	0.182	0.654	**0.673***	-0.080
	Pb	-0.099	0.180	0.381	0.552
	Fe	0.054	0.570	0.634	-0.293
	Cd	0.013	-0.011	0.145	0.536
Typha domingensis	**Sediments**				
	Metals	**Cu**	**Pb**	**Fe**	**Cd**
	Cu	-0.397	0.368	0.284	-0.151
	Pb	0.383	0.476	0.654	-0.830
	Fe	-0.049	0.873	0.654	-0.081
	Cd	-0.636	0.429	0.134	0.370

The significant values are in the bold letters**.** ***P**< 0.05

Table 10. Person correlation among heavy metal concentrations (µg/g dw) in plants of the two drains

	Cu	Pb	Fe	Cd
Cu	1			
Pb	0.006	1		
Fe	0.081	0.010	1	
Cd	-0.209	0.423	0.481*	1

*Correlation is significant at the 0.05 level (2-tailed).

5.3. Assessment of plants ability for heavy metal bioaccumulation

The ability of the three hydrophytes under research to take in and store heavy metals in their tissues was measured using the bioaccumulation factor (BAF). Aquatic plants may collect heavy metals as a result of biological factors (such as species, physiology and growth duration) or non-biological factors (such as temperature, season, salinity and pH), according to **Bonanno and Lo Giudice (2010)**. The BAF reveals how well the plant is able to remove heavy metals from the environment and identifies whether it is an excluder or an accumulator **(Bose *et al*., 2008)**. Heavy metal-accumulating plants had BAFs >1.0, while heavy metal-excluding plants typically had BAFs < 1.0 according to **Zhu *et al*. (2005)**. With a BAF >1.0 for all heavy metals in the current investigation, hydrophytes were identified as having a bioaccumulation procedure based on high levels of heavy metals in the root system. Among the hydrophytes that were studied along the two drains, the largest accumulation of each heavy metal was found in the floating hydrophyte *Eichhornia crassipes* (Fig. 7a).

BAF findings (Fig. 7b) showed that plant samples accumulated heavy metals in the following sequence: Pb > Cd > Cu > Fe for *P. australis* in the Kitchener Drain, while the ranking in the New Damietta Drain was Cd > Pb > Cu > Fe. However, according to BAF findings (Fig. 7c), plant samples accumulated heavy metals in the following sequence: Cu > Pb > Cd > Fe for *T. domingensis* in the Kitchener Drain, while the ranking in the New Damietta Drain was Cd > Pb > Fe > Cu. Generally, these observations are in harmony with the study of **El-Amier *et al*. (2018)**. With the exception of Cu, which accumulated more in the roots of *T. domingensis* in the Kitchener Drain, and Cd which accumulated more in the roots of *T. domingensis* in the New Damietta Drain, *P. australis* had the highest BAF value for all heavy metals in roots when compared to *T. domingensis* (emergent hydrophytes). Emergent hydrophytes have the greatest capacity to acquire a single heavy metal, but they do not have the greatest capacity to accumulate multiple heavy metals per the measured BAF values.

The distribution of heavy metals between the roots and aboveground organs of *T. domingensis*, *P. australis*, and *E. crassipes* is shown using the value of translocation factors (TF) (Fig. 8). According to the TF results (Fig. 8a), *P. australis* had a TF < 1 for

Cu, Pb, Fe, and Cd in all stations of the Kitchener Drain except station 1, which had a TF > 1 for Pb and Cd. *P. australis* also had TF < 1 for Cu, Pb, Fe, and Cd in all stations of the New Damietta Drain, except stations 6 and 7 for Pb and stations 7 and 9 for Cd, where the value was greater than one. Due to the results of *T. domingensis* (Fig. 8b), it had a TF < 1 for all the elements in the New Damietta drain. On the other hand, the Kitchener Drain had TF > 1 for Pb and Cd and TF < 1 for Cu and Fe. From Fig. (8c), the value of TF for *E. crassipes* was less than one for Fe and Cd in the two drains and Cu in the New Damietta Drain. Although it had TF greater than 1 for Pb in both drains, Cu was recorded in the Kitchener Drain and Cd in the New Damietta Drain. For phytostabilization, species with BAF values greater than 1 and TFs less than 1 might be appropriate. Species having BAFs = TFs greater than 1 may nevertheless be advantageous for phytoextraction **(Bello *et al*., 2018)**. For the plant species under examination, the TFs of the heavy metals were less than one; therefore, they are suitable for phytostabilization of these heavy metals, with the exception of *T. domingensis* and *P. australis* for Cd and Pb in some locations of the two drains and *E. crassipes* in some locations for Pb and Cu, where they are perhaps suitable for phytoextraction of these elements.

The TFs value below one suggested that the studied species had a slower rate of metal translocation, spreading from their below-ground tissues to their above-ground tissues. Due to this, the species under study accumulated heavy metals in their underground tissues rather than successfully transferring them from the roots to the rest of the plant. Thus, the examined plants may be used to phyto-stabilize metal-polluted sediment as metal excluders **(Ali *et al*., 2013; Duman *et al*., 2015)**. These findings agree with those of earlier research by **Cicero-Fernández *et al*. (2016)** and **Abdelaal *et al*. (2021)**. The main factor limiting the transfer of the investigated metals is their significant sequestration in the cortical tissues of roots, which is thought to be an adaptation for aquatic macrophytes **(Bonanno, 2013; Klink, 2017)**. Yet, the essential metals (e.g., Fe, Cu, Zn, and Mn) for plant metabolism are typically distributed differently in the aboveground tissues **(Klink, 2017)**. As a result, the tested species and tissues showed significant variation in the mobility and translocation of these metals.

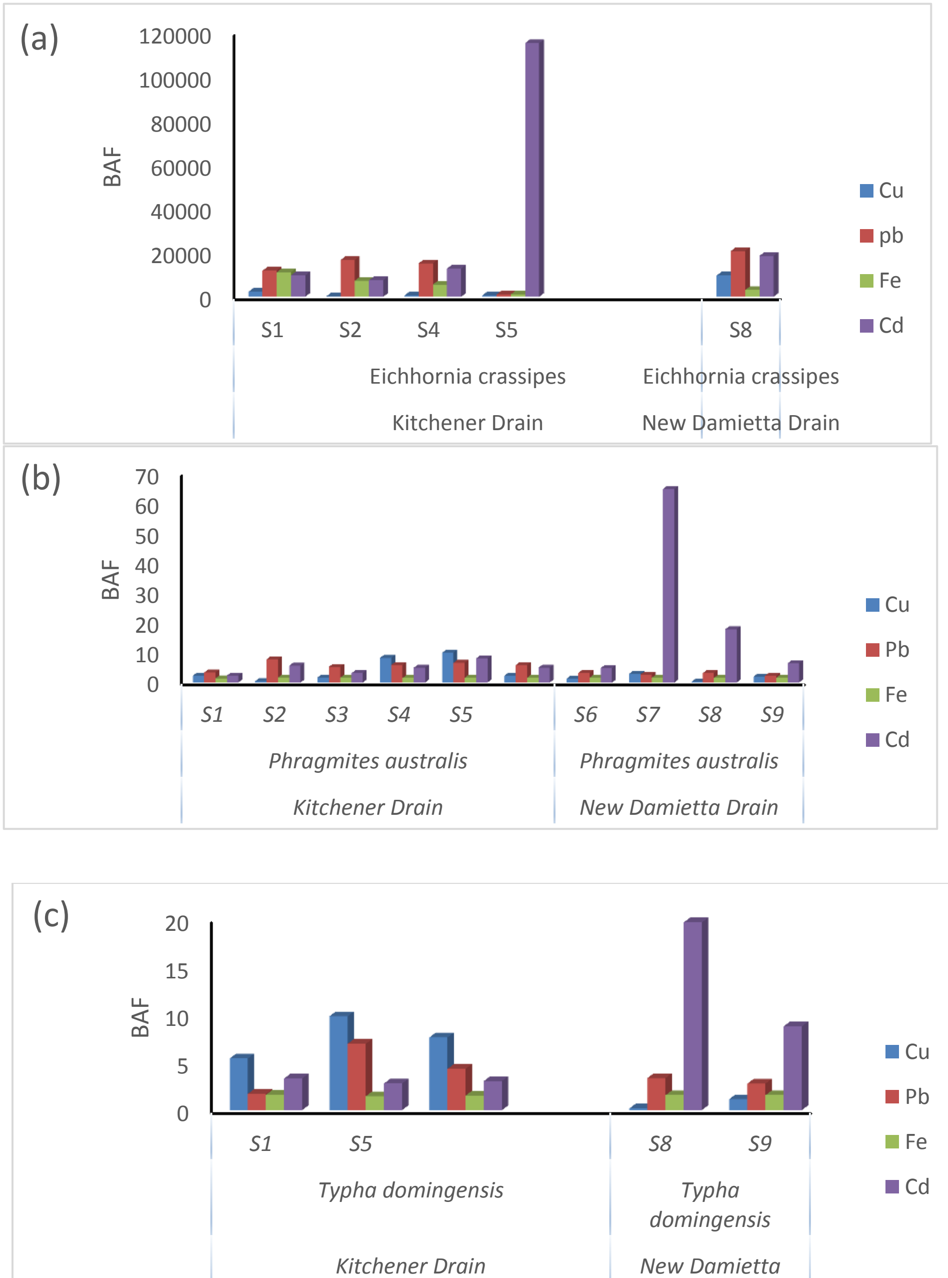

Fig. 7. Heavy metal bioaccumulation factor (BAF) (a) *E. crassipes*, (b) *P. australis* and (c) *T. domingensis* in both drains

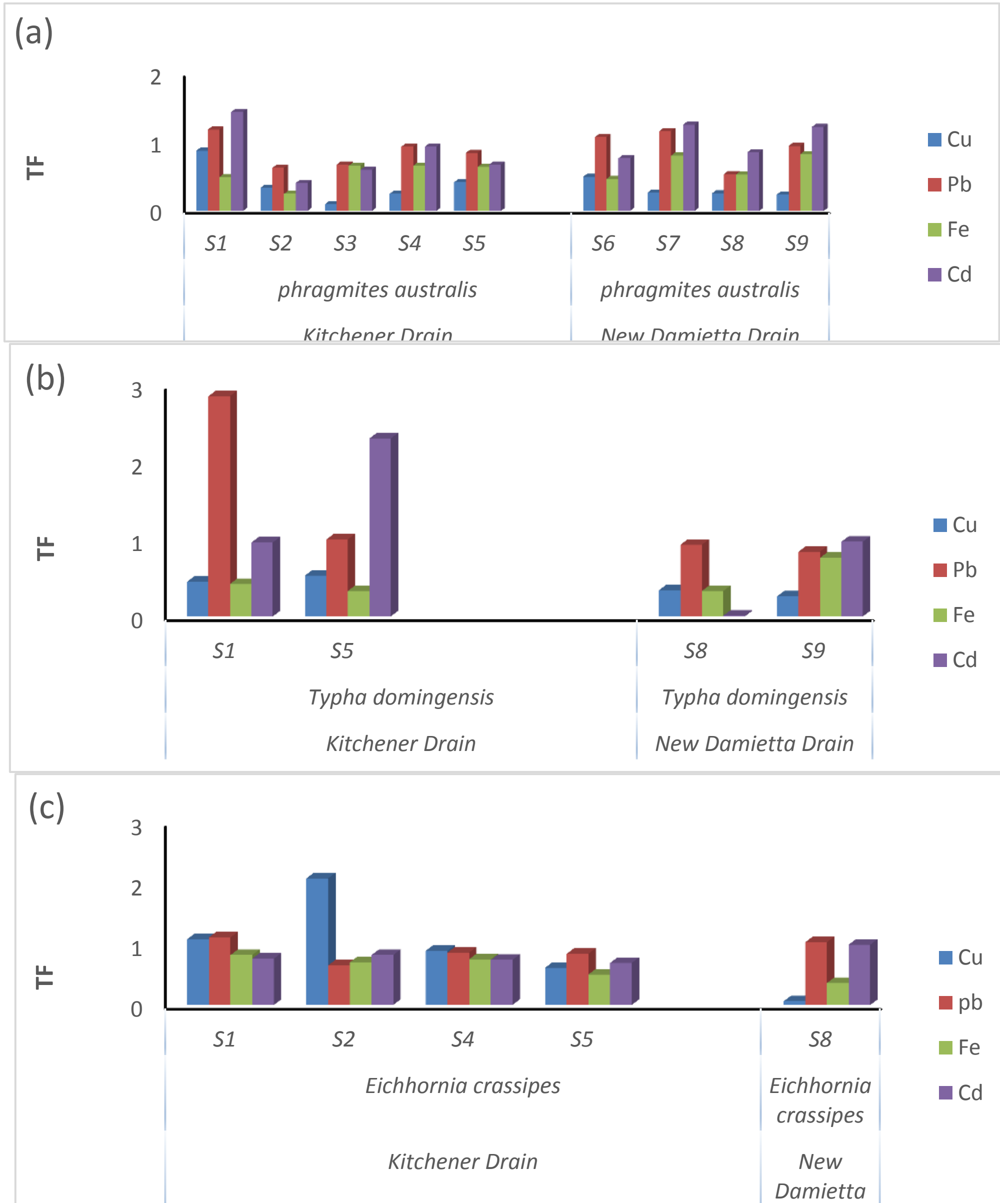

Fig. 8. The translocation factor (TF) of the three studied macrophytes grown along the two drains

CONCLUSION

The current study offers a thorough examination of the availability of heavy metals in water, sediment, and plant tissues in the New Damietta and Kitchener Drains. The results of heavy elements (Cu, Fe, and Cd) in both drains are within **EPA (2002)** and **WHO (2011)** limits, except for Pb, which exceeds the permissible limits. The risk assessment indices showed that Fe is the least likely metal to influence the pollution load, while Cd is the main pollutant to generate high pollution. The potential ecological risk increases in the Kitchener Drain compared to the New Damietta Drain. *E. crassipes* showed the highest accumulation for each of the heavy metals. *P. australis* has the greatest BAF value for all heavy metals in roots, with the exception of Cu and Cd, which accumulate more in the roots of *T. domingensis* in the Kitchener Drain and the New Damietta Drain, respectively. Given that these three macrophytes may be suggested as phytoremediators of the studied heavy metals, the present study highlights the significance of using the dominant macrophytes in the drains of the Nile Delta region to keep the heavy metal pollution in check and suggests phytoremediation as a promising, eco-friendly, and practical method for the removal of heavy metals from the polluted drains. To prevent any additional increase in harmful metals, it would be very important to implement awareness measures (such as regulating industrial sources) and a future-oriented strategy for minimizing pollution in both drains.

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