Journal of Soil Science and Plant Nutrition (2024) 24:8005–8015
https://doi.org/10.1007/s42729-024-02094-0

ORIGINAL PAPER

Typha domingensis (Pers.) Poir. ex Steud. Potential to Restore Contaminated Wetlands in Egypt

Manar A. Soliman[1] · Dalia A. Ahmed[2] · Khalid H. Mansour[3] · Fatma A. Gharib[3] · Tarek M. Galal[4] · Dalia F. Slima[5]

Received: 17 July 2024 / Accepted: 16 October 2024 / Published online: 8 November 2024
© The Author(s) 2024

Abstract

Several studies have reported *Typha domingensis* (Typhaceae) as a heavy metal (HM) hyperaccumulator. This study aims to assess the seasonal variations in the accumulation potential of *T. domingensis* (TD) for HM in polluted wetlands in Greater Cairo, Egypt. Sampling of fresh wild plants from the TD's subterranean (Root and stem) and surface components were gathered from different polluted sites distributed in the canal of Ismailia and Nahia drain, as well as from the River Nile as an unpolluted site (control). The findings showed that pollution negatively affected the chemical characteristics of sediment and water. Except for the TD's leaf area, there were significant seasonal variations in the growth characteristics (density, stem diameter, leaf length, and width, fresh and dry biomass). The subterranean parts stored higher amounts of HM than the aboveground shoots. Manganese (Mn) concentration (413.2 mg kg^{-1}) was greater in the roots of autumn plants, whereas their shoots recorded the highest Pb (225.8 mg kg^{-1}). Al, Cd, Cu, Fe, Ni, and Zn concentrations in summer plant roots (1499.9, 74.8,1356.1, 3948.8, 403.8, and 1294.2 mgkg^{-1}, respectively). The factor of metal bioaccumulation (BF) values, was high in TD plants growing in a polluted Ismailia canal, but translocation factor (TF) values for all measured elements were lower than one, except for Pb. Summer is the best season for TD growth to sequester high HM concentrations. The authors recommended that TD be employed to mitigate HM pollution in wetlands and restore them.

Keywords Cattails · Wetlands · Heavy metals · Monitoring · Contamination

1 Introduction

Water is the fundamental resource sustaining life on Earth (Dhir 2013). Physical, chemical, and biological contamination of water resulting from anthropogenic activities is a serious issue worldwide. Besides, municipal sewage discharge and industrial operations compromise water quality (Dhir 2013). Among the different types of pollutants, heavy metal contamination is of more significance due to its wide distribution (Ali et al. 2013). The contamination of aquatic ecosystems with heavy metals poses a significant hazard to aquatic organisms due to the fragility and limited self-cleaning ability of these systems relative to other ecosystems (Soner et al. 2017). According to Benson et al. (2016), most aquatic ecosystems in the world have been threatened and degraded by heavy metal pollution resulting from anthropogenic activities. The bioavailability of these metals in aquatic substrates, such as sediment, water, and aquatic macrophytes, is contingent upon their physicochemical forms (Benson et al. 2013). Also agricultural practices (e.g. adding chemical fertilizers or/and insecticides) are key

✉ Dalia A. Ahmed
dalia.ahmed@science.tanta.edu.eg; drdalia1080@yahoo.com

Manar A. Soliman
manar.alaa@women.asu.edu.eg

Tarek M. Galal
Tarekhelwan@yahoo.com

Dalia F. Slima
Dalia.fahmy@science.menofia.edu.eg; daliatr@yahoo.com

1 Botany Department, Faculty of Women for Arts, Science and Education, Ain Shams University, Cairo, Egypt

2 Botany and Microbiology Department, Faculty of Science, Tanta University, Tanta, Tanta 31527, Egypt

3 Botany and Microbiology Department, Faculty of Science, Helwan University, Cairo 11790, Egypt

4 Biology Department, Faculty of Science, Taif University, P.O. Box 11099, Taif 21944, Saudi Arabia

5 Botany and Microbiology Department, Faculty of Science, Menoufia University, Menoufia, Egypt

players in the rise of HM accumulation problems in water and soil (Oves et al. 2012; Hellal et al. 2019).

Wetlands serve as natural filters that mitigate the movement of contaminants via water, rendering them a viable, cost-effective solution for enhancing surface water quality (Farahat and Galal 2018). Investigating metal content in aquatic plants and sediments is essential for restoring, managing, and monitoring aquatic ecosystems (Eid et al. 2020a). By evaluating the association between a particular plant species and specific heavy metals, we will rehabilitate the natural functions of affected wetlands (Bonanno et al. 2017). Remediation of heavy metals from aquatic ecosystems usually requires expensive, energy-intensive, and metal-specific technologies such as reverse osmosis, ion exchange, electrodialysis, and adsorption (Bonanno et al. 2017). Since HMs are not biodegradable, HMs in soils can persist for a long time (Dökmeci 2020) and are difficult to remediate (Diagne et al. 2015).

Phytoremediation, a class of potential technologies (Pletsch 2003), which uses plants that accumulate metabolites for the removal of dangerous metals (Salt et al. 1995), witnessed a spike in popularity in the early 1990s. Numerous naturally occurring plants, including *Cyperus articulatus* (Farrag and Fawzy 2012; Galal et al. 2017a), C. *alopecuroides* (Batool et al. 2014; Moussa 2015; Galal et al. 2021, 2022), *Vossia cuspidata* (Farahat et al. 2021; Galal et al. 2017b; Awad et al. 2023), and *Portulaca oleracea* (El-Shamy et al. 2019), had been shown to exhibit phytoremediation potential to absorb HM from contaminated water sources and wetlands in Egypt. Therefore, using aquatic plants for this purpose is of great importance since it has long been known that these plants can accumulate heavy metals in degraded wetlands. Aquatic macrophytes as TD are effectively used for phytoremediation to mitigate toxic concentrations in heavy metals –contaminated aquatic ecosystems (Eid et al. 2020a).

Water cattail, or *Typha domingensis*, is a member of the Typhaceae family and is found in salty water environments, particularly in ditches and marshes. The rhizomatous perennial plant TD grows to a height of 1.5 to 3 m (Boulos 2005). To improve the water quality in treatment systems, TD is commonly used in constructed wetlands. It is widely distributed throughout Asia, Australia, North and South America, Africa, the tropics, subtropics, and warm temperate regions of Europe (Hadad et al. 2010; Eid et al. 2012a; Gomes et al. 2014; Mufarrege et al. 2014). Water cattails were used in many ecological contexts for a range of functions, such as the filtering of contaminated water and bank protection (Eid et al. 2012b; Ghazi et al. 2019).

The effectiveness of TD as a hyper-accumulator for several HMs (e.g. Cr, Cd, Ni, Pb, and Zn) has been demonstrated by several studies (Gomes et al. 2014; Mufarrege et al. 2014). It has also been shown to absorb and assemble Al and Fe (Hegazy et al. 2011). According to reports, drought, and salinity are among the environmental stresses that TD can withstand (Akhtar et al. 2017; Da Cunha Cruz et al. 2020; Akhter et al. 2021). Eid et al. (2012b) provided evidence of TD's capacity to collect HMs in its tissues, as well as the phytoextraction potential and amount of HMs released back into the water after the decomposition of dead tissues. Eid et al. (2012a) used TD as a bioindicator of water contamination in Lake Burullus, Egypt.

As wetlands are continuously contaminated due to various types of anthropogenic activities by various HMs, bioremediation using aquatic macrophytes is an effective method for treating contaminated wetlands. Our hypothesis is that *T. domingensis* can sequester large quantities of HMs and is a potential candidate for phytoremediation to restore contaminated wetlands. Consequently, our study was conducted to evaluate the seasonal potential of *T. domingensis* to treat contaminated wetlands and to assess the HM absorption efficiency of its polluted watercourses in Greater Cairo, Egypt.

2 Materials and Methods

2.1 Study Sites

In the present study, three sites were selected (1) River Nile in southern Cairo, (a control site). (2) The Ismailia Canal at Qalyubia Governorate is one of Egypt's most significant effluents of the Nile River, providing surface water for four governorates in the East Nile delta. Its length is 128 km, with a depth of 1–3 m and a width of 30–70 m. It is the main source of drinking and irrigation water for many cities. It is considered a polluted site as it receives industrial and agricultural wastes (Gharib et al. 2020). (3) Nahia drain at north Giza Governorate which gets contaminated water from industrial and agricultural practices in the neighboring villages (generated by the Abo-Rawash wastewater treatment facility) (Fig. 1).

2.2 Sampling Design

Sampling of TD plants were carried out seasonally through six polluted sites, distributed equally in Nahia drain and Ismailia canal, in the period from spring 2020 until winter 2021. As control samples, 2 unpolluted sites were selected during spring and autumn 2020 on the River Nile, and the average measurements were used to compare with those of the polluted sites. The distance between every two sites was kept even as much as possible according to the presence of the target species. In each site, three distinguishable

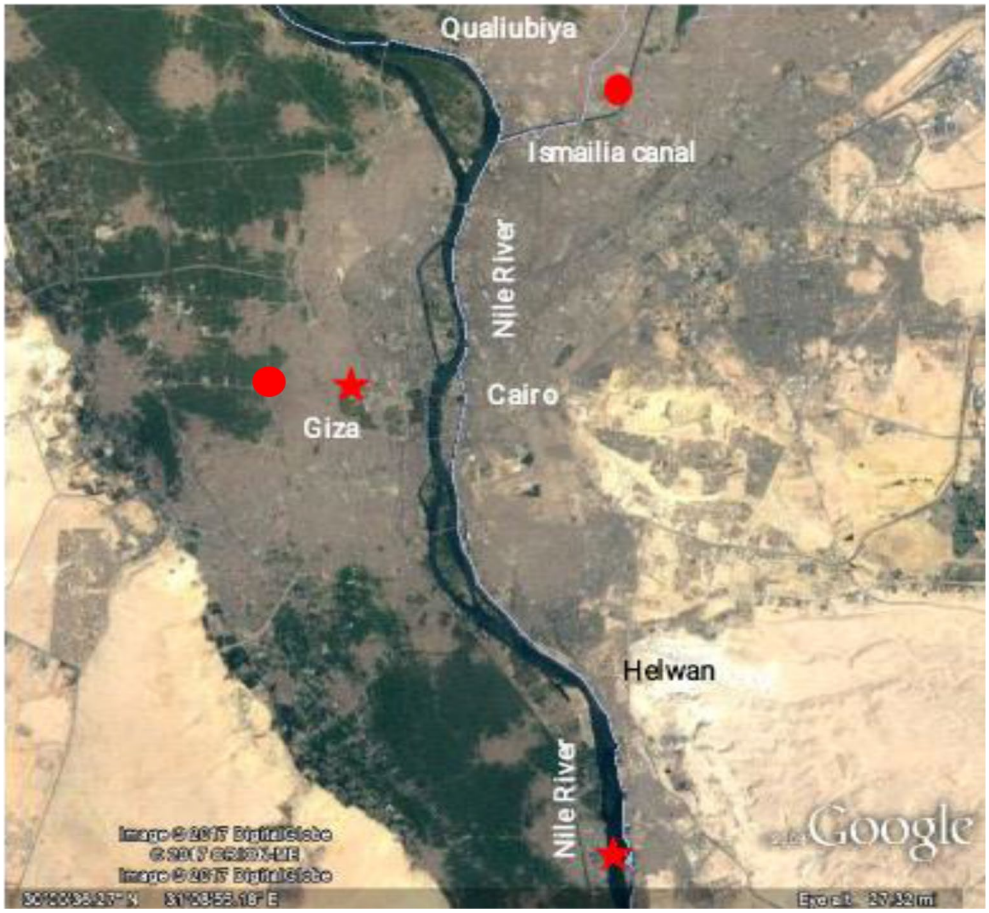


Fig. 1 Location map showing the polluted (●) and the unpolluted (★) site of the study area. 30° 00′ 36.27″ N and 31° 08′ 5.18″ E. Source: Google Earth 29 April 2021

and randomly placed quadrats lied within 1–3 m from the shore in the wateredge habitat (each 1 m^2, $n = 72$ in polluted, and (12) in control watercourses), were used to collect the aboveground parts (leaves and inflorescences). Care was taken to ensure that the distance between each two quadrats were less than 2 m. The identical quadrats were harvested at a depth of 50 cm, and the subterranean components (roots and rhizomes) were collected and then divided into roots and rhizomes and stored in plastic bags in an ice box until they were transported to the laboratory. In the laboratory both subterranean and aboveground parts were rinsed by deionized water to remove HMs left on the plant parts. After cleaning plant parts were dried at 85 °C using an electrical oven until a constant weight was achieved then ground into particles < 0.4 mm to analyze for HMs (Slima and Ahmed 2020).

2.3 Water and Sediment Sampling and Analysis

Between the spring of 2020 and the winter of 2021, three composite samples from each study location were collected, transported to the laboratory for examination, and then refrigerated. According to Rowell (1994), the acidity and salinity of the filtered water samples were determined using pH and electrical conductivity meters (SevenExcellence pH meter S400 and Jenway 4510 Conductivity/TDS Meter, respectively). After acidifying the filtered water samples with hydrochloric acid, the amounts of Al, Cu, Cd, Cr, Fe, Ni, Mn, Zn, Pb, and Co were estimated using a Younglin AAS 8020 Atomic absorption Spectrophotometer (APHA 2005). Also, three composite samples of sediments were collected from each site at a depth of 0 to 50 cm, maintained in a stainless steel crab for drying, and then sieved using a 2 mm sieve. To determine the pH, EC, and the total nitrogen content, sediment extract (1:5 w/v) was made. Sediment samples were digested in 20 ml of HNO_3:$HClO_4$:HF (1:1:2 V: V:V) and then calculate HMs concentration (Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn, and Co) using a Perkin-Elmer 3100 Atomic Spectrophotometer (Allen 1989; APHA 2005).

2.4 Growth Parameters

Plant density (ind. /m^2) and stem diameter (cm) were calculated for the collected plants from the different studied sites. Five randomly collected plants from every quadrate were transported to the lab in plastic bags. The samples were carefully rinsed several times with distilled water to remove

debris. Some morphological traits were measured, {both leaf length and width (cm)}, leaf area (cm^2), and fresh and dry weights (g/m^2) for each plant sample. The average fresh and dry weights were then multiplied by the plant density to determine the fresh and dry biomass (g/m^2), respectively.

2.5 Plant Heavy Metals

From the collected TD samples, three composite samples from every location were divided into subterranean and aboveground parts. The parts were oven-dried and homogenized. One gram from every sample was digested using a 20 ml tri-acid mixture HNO_3:$HClO_4$:HF (1:1:2 V: V:V) (Lu 2000). The concentrations of the HMs (Al, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn, and Co) were measured as described in water sample analysis Sect. 2.3.

2.6 Plant Pigments

To construct three composite samples for each location, three green top leaves were collected from each quadrat and mixed. Two grams from fresh leaves were homogenized in 90% acetone (v/v) before being analyzed spectrophotometrically at 453, 644, and 663 nm with aqueous acetone used as a control (Allen 1989). The following equations were used to determine the concentration of chlorophyll and carotenoids:

The formula for chlorophyll a is 10.3E663–0.918E644, for chlorophyll b is 19.7E644–3.87E663, and for carotenoids is 4.2E453 - (0.0264 chl a + 0.426 chl b), where E is the absorbance at a certain wavelength (nm).

2.7 Data Analysis

A paired-sample t-test was used to determine the significance of the analyzed variables for water, sediment, and plant parts at the studied locations. We analysed the discrepancies in the results' normality and similarity. The minimum, maximum, mean, and coefficient of variance (CV %= SD/Mx100) for sediment and water samples were calculated. Using the SPSS (2012) software (version 21), ANOVA (One-way analysis of variance), and Duncan's test for average multiple comparisons were used to assess the significance of changes in HMs in various plant parts.

The ability of a plant organ to keep a certain HM to its soil concentration is known as **BF** and is calculated using the formula: C_{root}/C_{soil}, where C_{root} and C_{soil} stand for the HM concentrations in the root and soil, respectively. According to the following equation, the **TF** represents the proportionate translocation of HMs from a plant's root to its shoot: According to Ahmed et al. (2023), TF is equal to C_{shoot}/C_{root}, where C_{shoot} and C_{root} stand for the HM concentration in the plant's shoot and root, respectively.

3 Results

3.1 Sediment and Water Properties

The chemical properties of the water and sediment were altered by pollution. Electric conductivity (salinity) values in polluted sediment and water were greater than those in unpolluted sediment and water (486.4 and 452.0 µS cm^{-1}, respectively). Additionally, a greater amount of pollutants caused the pH to be decreased. Except for Cd, Fe, Mn, Ni, and Pb, the statistical analysis of chemical characteristics for sediment and the majority of water variables revealed substantial differences between polluted canals and unpolluted rivers (Table 1). The sediment also collected more HMs than the water did. The HM concentrations were in the following order: In the water, they were Al > Cu > Fe > Cr > Co > Zn > Mn > Ni > Cd > Pb, but in sediment, they were Fe > Al > Cu > Mn > Zn > Cr > Ni > Pb > Co > Cd.

3.2 Growth Properties

The results of the current study showed that TD plants' growth parameters (except leaf area) changed dramatically seasonally (Table 2), with certain parameters having substantially greater values in the control river. Summer populations had the highest values of plant density, diameters, and dry and fresh weight of above-ground parts (2.7 Ind. m^{-2}, 10.1 cm, 370.8 gm^{-2} and 904.4 gm^{-2} respectively); whereas autumn populations had the greatest leaf lengths, widths, and areas (55.7 cm, 31.3 cm, and 1832.1 cm^2, respectively). In contrast, winter was the most diminishing season for growth performance.

Significant differences could be seen in the TD's seasonal pattern for biomass (Fig. 2). The greatest fresh and dry biomass values were found in plants collected in the summer (1674.4 and 777.9 g m^{-2}, respectively), while the lowest values were found in plants collected in the winter (1319.6 and 551.6 g m^{-2}). Furthermore, compared to the polluted canals, the fresh and dry biomass of TD in the control River Nile significantly increased.

3.3 Plant Heavy Metals

The one-way analysis of variance (ANOVA-I) statistical analysis revealed a substantial annual change in the concentrations of all HMs under investigation (Table 3). It was evident that the plant underground parts gathered more HMs than their aboveground branches did. Fe, Al, Cu, Zn, Ni, and

Table 1 Chemical characteristics of the sediments and water of the polluted and unpolluted canals. CV: coefficient of variation, EC: Electric conductivity

Variable	Sediment								Water							
	Polluted				Unpolluted			t_{value}	Polluted				Unpolluted			t_{value}
	Min	Max	M ± SD	CV (%)	Min	Max	M ± SD	CV (%)		Min	Max	M ± SD	CV (%)	Min	Max	M ± SD	CV (%)	
pH	4.6	5.4	5.0 ± 0.4	8.0	6.8	7.2	7.0 ± 0.2	2.9	**2.6***	7.1	8.0	7.6 ± 0.4	5.3	5.9	6.7	6.3 ± 0.4	6.3	**2.5***
EC (µS cm^{-1})	477.1	494.7	486.4 ± 8.8	1.8	390.6	399.2	392.7 ± 2.9	0.7	**2.8***	442.9	462.1	452.0 ± 9.6	2.1	255.4	275.8	265.6 ± 10.2	3.8	**3.4***
Heavy metals	**mg kg^{-1}**									**mg l^{-1}**								
Al	8305.3	8704.9	8505.2 ± 199.8	2.3	3065.1	3247.8	3156.5 ± 91.4	2.9	**5.2***	0.50	0.53	0.516 ± 0.016	3.1	0.16	0.18	0.165 ± 0.010	6.1	**2.9***
Cd	1.3	1.7	1.5 ± 0.2	13.3	0.5	0.6	0.6 ± 0.1	16.7	**2.7***	0.005	0.007	0.006 ± 0.001	16.7	0.001	0.003	0.002 ± 0.001	50.0	**1.1**
Cr	17.3	22.0	19.5 ± 2.5	12.8	9.3	13.7	11.4 ± 2.2	19.3	**3.4***	0.09	0.11	0.095 ± 0.010	10.5	0.002	0.003	0.002 ± 0.001	50.0	**3.2***
Cu	345.4	381.6	361.1 ± 18.2	5.0	171.5	182.8	177.3 ± 5.7	3.2	**3.3***	0.30	0.32	0.307 ± 0.009	2.9	0.01	0.02	0.012 ± 0.010	83.3	**4.2***
Fe	10032.4	12100.3	11065.1 ± 1033.9	9.3	5845.2	6465.1	6144.7 ± 310.5	5.1	**4.8***	0.09	0.10	0.096 ± 0.005	5.2	0.04	0.06	0.045 ± 0.010	22.2	**1.7**
Mn	297.3	311.3	305.0 ± 7.1	2.3	110.1	120.3	115.3 ± 5.1	4.4	**4.4***	0.04	0.06	0.045 ± 0.010	22.2	0.01	0.02	0.015 ± 0.001	6.7	**1.3**
Ni	16.4	20.4	18.4 ± 2.1	11.4	8.0	8.3	8.1 ± 0.2	2.5	**6.1***	0.040	0.042	0.041 ± 0.001	2.4	0.03	0.05	0.042 ± 0.010	23.8	**0.4**
Zn	44.2	61.2	52.2 ± 8.5	16.3	21.5	27.8	24.6 ± 3.2	13.0	**3.4***	0.05	0.06	0.056 ± 0.006	10.7	0.01	0.02	0.015 ± 0.005	33.3	**2.6***
Pb	13.4	21.5	17.6 ± 4.1	23.3	3.9	4.6	4.2 ± 0.4	9.5	**2.8***	0.002	0.004	0.003 ± 0.001	33.3	0.001	0.002	0.001 ± 0.001	100.0	**1.4**
Co	6.8	7.8	7.3 ± 0.5	6.8	3.1	4.0	3.6 ± 0.5	13.9	**3.7***	0.078	0.080	0.079 ± 0.001	1.3	0.002	0.004	0.003 ± 0.001	33.3	**2.6***

Cd concentrations in summer plants' roots were the highest (3948.8, 1499.9, 1356.1, 1294.2, 403.8, and 74.8 mg kg^{-1}, respectively), whereas Co concentrations in their shoots were the lowest (18.4 mg kg^{-1}). Autumn plants also had the highest concentrations of Mn in their roots (413.2 mg kg^{-1}), the highest concentration of Pb in their shoots (225.8 mg kg^{-1}), and the lowest amounts of Cd, Fe, and Ni (5.9, 728.3, and 116.4 mg kg^{-1}, respectively) in their leaves. Additionally, the roots of winter plants had the highest concentrations of Co and the lowest quantities of Pb (124.9 and 20.9 mg kg^{-1}, respectively), but their shoots had the lowest concentrations of Al, Cr, Mn, and Zn (154.2, 7.7, 134.1, and 116.5 mg kg^{-1}, respectively). The spring roots also had the greatest amount of Cr (47.4 mg kg^{-1}). When compared to the control Nile, the shoots and roots of the TD collected noticeably larger levels of HMs from the polluted canal (Table 4). In comparison to the shoots, the roots collected all HMs, except Pb.

3.4 Plant Pigments

The analysis of TD leaf pigments grown in polluted canals and drains indicated a significant decline in chlorophyll b and carotenoid content (Fig. 3). Chlorophyll b was reduced by 32%, while carotenoids were reduced by 28% compared to the control samples.

3.5 Heavy Metal Bioaccumulation and Translocation

Although TF values for all studied elements, except for Pb, were less than one, metal BF values were often higher in *Typha* plants and raised in polluted canals (Table 5). The results showed that TD plants were hyper-accumulators for Zn, Fe, and Cd in their roots, with BF values (15323.08, 28385.42, and 9017.14, respectively) for plants grown up in polluted water.

Along with the other HMs that were studied, Mn had the highest BF value (8017.77), followed by Zn (7573.52), Ni (3758.47), and Al (2456.55). Since the TF values for every element under investigation were less than one, the results indicated that *Typha* plants had little to no strategy for collecting HMs in their shoots (Table 5).

4 Discussion

Ecosystems and the natural environment have been damaged by the worldwide deterioration of land brought on by heavy metal contamination (Chen et al. 2015). According to the current investigation, the salinity of contaminated sediment and water was higher than the control. Pollution

Table 2 Seasonal variation of morphological characteristics of *Typha domingensis* in polluted and unpolluted canals. Maximum and minimum values are underlined

Variable	Polluted site				Unpolluted Site	F-value
	Spring	Summer	Autumn	Winter	Nile	
Density (Ind. m^{-2})	2.2 ± 0.9abc	*2.7 ± 0.7ab*	2.3 ± 0.8bc	*1.9 ± 0.7c*	3.0 ± 0.0a	7.6**
Diameter (cm)	8.6 ± 1.6b	*10.1 ± 2.9a*	9.6 ± 2.1ab	*7.4 ± 1.1b*	7.9 ± 1.3b	11.9**
Leaf length (cm)	53.5 ± 26.2ab	54.2 ± 13.9ab	*55.7 ± 15.1ab*	*45.1 ± 12.6b*	56.2 ± 10.3a	3.8*
Leaf width (cm)	29.9 ± 14.3ab	30.5 ± 7.7ab	*31.3 ± 8.3ab*	*25.5 ± 6.8b*	31.5 ± 5.8a	3.8*
Leaf area (cm^2)	1804.9 ± 3707.5a	1805.4 ± 928.1a	*1832.1 ± 127.0a*	*1215.8 ± 754.7a*	1818.8 ± 606.3a	1.4^{ns}
Fresh weight (g $m^{-2)}$	785.6 ± 39.9bc	*904.4 ± 61.8a*	833.2 ± 33.8ab	*630.1 ± 43.7c*	871.2 ± 62.0ab	13.2**
Dry weight (g m^{-2})	309.9 ± 20.1b	*370.8 ± 34.2a*	339.2 ± 16.3ab	*265.2 ± 15.8b*	388.0 ± 35.0a	8.9**

Means with the same letters are not significant according to Duncan's test at $P \geq 0.05$. * $p < 0.01$, ** $p < 0.001$, ns: not significant

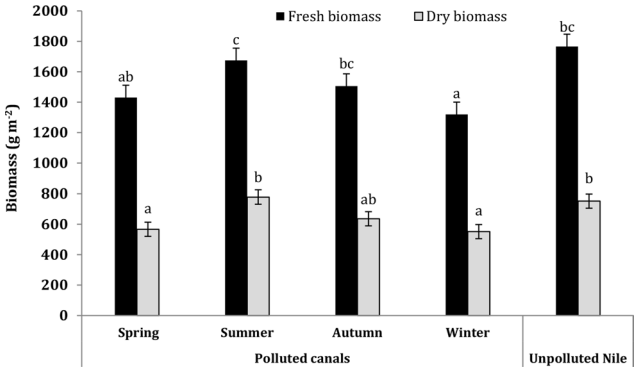


Fig. 2 Fresh and dry biomass of the above-ground parts of *Typha domingensis* collected from the polluted canal and unpolluted river. Means with the same letters are not significant according to Duncan's test at $P \leq 0{,}05$. Vertical bars are standard errors

also significantly decreased pH. Sarwar et al. (2017) stated that several factors, such as pH, ion concentration, and plant species, influence the bioavailability of metals in sediments. So, the low pH of the contaminated sediments may cause an increase in metal solubility and availability in the sediments of the contaminated canals. Following Balkhair and Ashraf (2016), HM mobility is greater at pH 7 than at pH > 7, which could account for the higher HM concentration in sediments compared to water. These results corroborated those of Allen (1989), Nagajyoti et al. (2010), and Chiroma et al. (2014), who found that contaminated watercourses included a hazardous spectrum of HMs. According to Norah (2014), low sediment pH (4.0 to 5.5) enhanced the availability and solubility of HMs such as Fe, Mn, Zn, Cu, and Co in a badly contaminated canal. High and neutral sediment pH values stabilize harmful components by lowering their bioavailability and solubility (Badr et al. 2012).

In the present study, it was clear that summer was the blooming season in contaminated areas and winter was the weathering season with the least amount of growth, in contrast to the unpolluted areas, which only showed marginal growth. This result agreed with the results of several aquatic macrophytes, where winter is the diminishing growth season, These macrophytes included *Eichhornia crassipes* (Odjegba and Fasidi 2007; Ajayi and Ogunbayo 2012), and *Echinochloa stagnina* (Shaltout et al. 2010), *Desmostachya bipinnata* and *Imperata cylindrica* (Shaltout et al. 2013), *Pistia stratiotes* (Galal et al. 2018; Tabinda et al. 2020), *Ludwigia stolonifera* (Galal et al. 2019) and *alopecuroides* (Batool et al. 2014).

According to Batool et al. (2014), HMs can cause physiological and morphological modifications in plants that inhibit their growth. The growth of TD in the control River Nile was, on average, much higher than in the polluted watercourses. The improvement or decrease in TD development parameters over different seasons may be attributed to high concentrations of HMs, which cause multiple metabolic changes. *Arundo donax* (Cristaldi et al. 2020; Galal and Shehata 2016; Eid et al. 2016), C. *articulates* (Farrag and Fawzy 2012; Galal et al. 2017a), V. *cuspidata* (Galal et al. 2017b), and *Ranunculus sceleratus* (Farahat and Galal 2018; Ievinsh et al. 2022) all showed similar results. The biomass for TD revealed a seasonal tendency, with plants collected in the summer having the highest fresh and dry biomass levels and those collected in the winter having the lowest. This finding was in agreement with Galal and Shehata (2016) who reported that eco-physiological restrictions, such as modifications to watercourse management practices, short growth seasons, low temperatures, the trophic status of the water, and adverse factors including pollution, competition, and animals, were to blame for the low plant biomass. Additionally, compared to the control; the yearly average biomass of TD increased dramatically in polluted canals, This finding also agreed with the result of Galal et al. (2021).

The analysis of TD leaf pigments indicated that the highest chlorophyll a value was recorded in the polluted canals. This may be a result of the low pH of polluted sediments, which increases the availability of iron. According to Naested et al. (2004), the generation and maintenance of chlorophyll as well as the structure and functionality of the chloroplast are all impacted by the Fe concentration in plants. According to Guo et al. (2022), inadequate Fe levels and an unbalanced medium pH impeded plant growth.

Table 3 Seasonal variations (Mean ± SD) of heavy metal concentrations (mg kg^{-1}) of the below- (R) and above-ground parts (S) of *Typha domingensis* collected from polluted canals. Maximum and minimum values are underlined

Season		Heavy metal									
		Al	Cd	Cr	Cu	Fe	Mn	Ni	Zn	Pb	Co
Spring	**R**	1042.9 ± 292.9b	53.3 ± 21.7b	*47.4 ± 20.1a*	928.6 ± 155.2c	2008.5 ± 752.4b	342.3 ± 168.5abc	318.1 ± 318.1ab	864.9 ± 242.1b	33.4 ± 46.4b	46.4 ± 31.3b
	S	211.7 ± 40.3c	8.8 ± 5.2d	8.1 ± 3.5b	*162.7 ± 39.1e*	808.6 ± 549.4c	153.9 ± 108.2 cd	145.7 ± 109.2b	250.9 ± 107.0 cd	53.7 ± 33.6b	18.5 ± 8.8b
Summer	R	*1499.9 ± 376.1a*	*74.8 ± 7.4a*	39.4 ± 31.9a	*1356.1 ± 259.6a*	*3948.8 ± 615.2a*	351.3 ± 158.9ab	*403.8 ± 199.9a*	*1294.2 ± 554.5a*	79.1 ± 79.5b	23.4 ± 15.3b
	S	288.1 ± 54.0c	10.7 ± 2.0d	32.9 ± 22.0ab	227.0 ± 52.5de	1684.2 ± 374.9bc	218.0 ± 54.7bcd	197.3 ± 92.9ab	251.1 ± 111.7 cd	138.7 ± 122.3ab	*18.4 ± 15.1b*
Autumn	R	1490.8 ± 541.9a	40.7 ± 9.1c	36.7 ± 34.0ab	1055.2 ± 243.2bc	2724.9 ± 578.9b	*413.2 ± 254.8a*	238.3 ± 102.9ab	835.3 ± 207.9b	30.7 ± 27.7b	100.9 ± 42.9a
	S	280.4 ± 154.2c	*5.9 ± 1.7d*	23.9 ± 18.3ab	186.8 ± 36.9e	*728.3 ± 253.1c*	152.6 ± 107.7 cd	*116.4 ± 74.2b*	128.0 ± 81.6d	*225.8 ± 259.6a*	37.5 ± 26.4b
Winter	R	1039.9 ± 242.7b	41.8 ± 6.7c	46.6 ± 20.5a	1270.4 ± 331.2ab	2217.9 ± 604.1b	336.5 ± 132.9abc	275.9 ± 198.6ab	458.5 ± 187.2c	*20.9 ± 19.6b*	*124.9 ± 77.5a*
	S	*154.2 ± 40.3c*	7.0 ± 2.5d	*7.7 ± 3.8b*	448.7 ± 287.6d	2055.2 ± 2343.8b	*134.1 ± 104.2d*	177.1 ± 143.5b	*116.5 ± 66.5d*	45.1 ± 30.4b	34.6 ± 16.9b
F-value		**26.5*****	**46.7*****	**3.1****	**34.9*****	**6.7*****	**3.4****	**2.3***	**18.3*****	**2.5***	**7.5*****

Means with the same letters are not significant according to Duncan's test at $P \geq 0.05$. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

They also revealed that chlorosis of early leaves is the most frequent indicator of Fe deficiency in plants. Additionally, the River Nile (control) included the highest levels of chlorophyll b and carotenoids, while the leaves residing in polluted canals contained the lowest levels of these pigments. These results agreed with the results of Galal et al. (2017a,b, 2021). The high HMs concentration, following Zhang et al. (2006), may inhibit chlorophyll b production and disrupt the photosynthetic process, hence reducing the nutrients required for plant life. Additionally, Manios et al. (2003) noted that under HM stress, which hydrolyzes chlorophyll, the chlorophyll b level in *T. latifolia* growing in polluted locations decreased considerably.

According to Bonanno and Lo Giudice (2010) and Sharma et al. (2006), biological parameters including species, plant age, and generation time, can affect the capacity of plants to restore metals. This can interpret why TD's underground parts restore more HMs than its above-ground shoots. Summer plant roots included the highest quantities of Al, Cd, Cu, Fe, Ni, and Zn. The results of this study align with those of Rezania et al. (2019) regarding *Phragmites australis* and Eid et al. (2020b) regarding TD. These studies indicated that the reason for the low levels of HM in above-ground plants could be attributed to the restricted movement of HM from below-ground to above-ground plant parts during the summer growing season. Furthermore, a plant's ability for seasonal accumulation may be influenced by seasonal variations in compartmentalization efficiency as well as physiological activity (Galal et al. 2017b). In the present study, summer is considered the TD growing season and this result follows the study of Karunaratne et al. (2003), Zhao et al. (2013), and Galal et al. (2021) who indicated that the development of aquatic macrophytes plants often flourished during the summer (the biomass was highest) and decreased during winter (the biomass was lowest). The shoots and roots of the TD gathered far more HMs from contaminated watercourses than did in the uncontaminated Nile. All of the heavy metals (HMs) were gathered in the below-ground portions, except for Pb, which was higher in the shoots. Aquatic plants often use the HM compartmentalization strategy, which includes accumulating large concentrations of HMs in their subterranean components, to protect themselves from the detrimental effects of metal toxicity (Bonanno et al. 2017).

The BF and TF could be utilized to estimate the potential of the plant for phytoremediation (Eid et al. 2019). The BF was utilized to evaluate the relationship between HM concentrations in sediments and plant tissues (Eltaher et al. 2019). Generally, it shows the translocation of HMs from the sediments to the plant root, which indicates the uptake potential of available metals from the environment, indicating whether the plant is an excluder, accumulator,

Table 4 Heavy metal concentrations (mg kg^{-1}) (Mean ± SD) of the different organs of *Typha domingensis* collected from polluted canals (P) and unpolluted (U) river

Heavy metal	Root		t-value	Shoot		t-value
	P	U		*P*	U	
Al	1268.4 ± 262.1	443.6 ± 200.1	**7.4****	233.8 ± 63.4	134.5 ± 54.2	**7.1****
Cd	52.6 ± 15.8	35.4 ± 6.8	**4.7***	8.1 ± 2.6	6.5 ± 2.4	**1.1**^{ns}
Cr	42.5 ± 5.3	13.8 ± 3.5	**4.3***	18.2 ± 12.4	6.0 ± 1.0	**4.2***
Cu	1152.6 ± 195.8	513.8 ± 208.6	**11.4*****	256.3 ± 130.9	217.7 ± 150.2	**2.8**^{ns}
Fe	2725.0 ± 869.5	1809.5 ± 299.3	**8.6****	1319.1 ± 654.4	720.3 ± 238.4	**3.5***
Mn	360.8 ± 35.5	178.3 ± 82.5	**6.3****	164.7 ± 36.7	114.6 ± 61.3	**3.7***
Ni	309.0 ± 713.1	166.5 ± 124.9	**9.6****	159.1 ± 35.5	327.6 ± 173.1	**5.2***
Zn	863.2 ± 341.7	511.0 ± 191.9	**3.8***	186.6 ± 74.5	243.4 ± 71.3	**7.8****
Pb	41.0 ± 25.9	68.4 ± 27.1	**2.3**^{ns}	115.8 ± 84.6	19.9 ± 11.4	**11.4*****
Co	73.9 ± 47.0	41.1 ± 16.8	**4.1***	27.3 ± 10.2	13.0 ± 5.2	**4.6***

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. ns: not significant

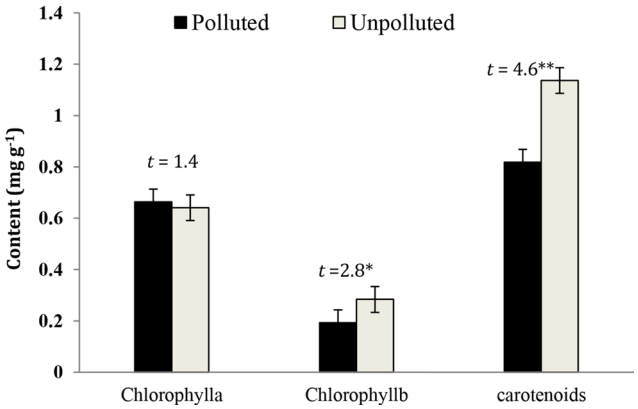


Fig. 3 Photosynthetic pigments content of the leaves of *Typha domingensis* grown on polluted (canal and drain) and non-polluted river. Vertical bars are standard errors. *$P \leq 0{,}05$ and **$P \leq 0.01$

Table 5 Bioaccumulation (BF) and translocation (TF) factors for heavy metals in *Typha domingensis* plants grown in Nile water as control and polluted canals

HMs	Unpolluted water		Polluted canals	
	BF	TF	BF	TF
Al	2688.4	0.30	2456.55	0.18
Cd	19666.67	0.18	9017.14	0.15
Cr	6000	0.43	447.36	0.42
Cu	42816.67	0.42	3758.47	0.22
Fe	40211.11	0.39	28385.42	0.48
Mn	12296.55	0.64	8017.77	0.45
Ni	3964.286	**1.96**	7573.52	0.51
Zn	34066.67	0.47	15323.08	0.21
Pb	51300	0.29	932.2	**2.82**

or indicator (Eid et al. 2019). The BF values for all investigated HMs were higher in below-ground parts in *Typha* plants grown in polluted watercourses, which indicated that TD accumulated HMs in their roots These findings are in agreement with that of Weis and Weis (2004), Barbosa et al. (2015), Galal and Shehata (2016), Ghazi et al. (2019) and Eid et al. (2012, 2020b). The current study indicated that TD had the potential to immobilize HMs in roots, while it can translocate only Pb (TF for all estimated HMs (except Pb) was < 1). Similar findings were mentioned by Eid et al. (2012). The higher translocation fraction of Pb in TD shoots makes them suitable for Pb phytoextraction from water and sediments. The studied plant's effectiveness in phytostabilizing metals was demonstrated by the high BF and low TF values. Phytostabilization is one of the phytoremediation approaches where the plant has a high BF coupled with low TF (Bello et al. 2018). While plants with BF and TF > 1 may be suitable for phytoextraction of metals (Sellal et al. 2019). So, TD has the potential to phytoextract Pb, whereas phytostabilizes all other studied HMs. According to these findings, TD is suitable for reducing HM pollution of wetlands. which played an important role in the development of the country in ancient times as well as now. The ancient Egyptians gave great importance to agriculture, as Egypt has been a large agricultural country for a long time and agriculture is dependent on the Nile River. Nile River is the main source of drinking water and supplies all watercourses in Egypt (serves as).

5 Conclusion

This study concluded that *Typha domingensis*, commonly known as cattail is a highly effective phytoremediator plant for wetlands. It has a wide tolerance, that it can thrive in a variety of wetland conditions, including those with high levels of pollutants. They are tolerant to heavy metals (Al, Cd, Cr, Cu, Fe, Mn, Ni, Zn, Pb, and Co), and even saline waters. Their deep root system allows them to access pollutants from the soil and groundwater, effectively removing them from the environment. It grows rapidly and produces large amounts of biomass (summer is the best growth season); this rapid growth facilitates the uptake and removal of pollutants. Cattails use several mechanisms to remove

pollutants from the environment, including Phytoextraction: The plants absorb pollutants from the soil and water through their roots and accumulate them in their tissues and Phytostabilization: Cattails immobilize pollutants in the soil, preventing their further movement and leaching into groundwater and can remove pollutants from water as it passes through their root zone (translocation factor values for all studied elements, except for Pb, were less than one, metal bioaccumulation factor values were often higher than 1). So, Cattails can be used to restore degraded wetlands by removing pollutants and improving water quality. They can be employed in constructed wetlands for the treatment of municipal and industrial wastewater. Overall, *Typha domingensis* is a valuable and versatile phytoremediator plant for wetlands. Its ability to tolerate harsh conditions and remove various pollutants makes it a promising tool for environmental remediation. Finally, plant roots must be harvested at the end of the summer season after maximum accumulation of heavy metals. The harvested biomass could be used commercially as a source of heavy metals, a substrate for biogas production, or be packed safely after burning to ash.

Author Contributions Tarek M. Galal and Dalia Abd El-Azeem Ahmed: conception and design, acquisition, analysis, statistic analysis and interpretation of results. Also, drafting the article and revising it. They approved the final version to be submitted for publication. Dalia F. Slima and Manar A. Soliman: Design, acquisition, analysis, statistic analysis and interpretation of results. Also, drafting the article and revising it. They approved the final version to be submitted for publication. Fatma A. Gharib and Khalid H. Mansour:: drafting the article and revising it. They approved the final version to be submitted for publication.

Funding This research was funded by Taif University, Saudi Arabia, project number (TU-DSPP-2024-171). Article processing charge (APC) is completely covered according to Springer Nature's fully open access agreements (Transformative Agreement between Springer Nature and Science, Technology & Innovation Funding Authority (STDF) in cooperation with Egyptian Knowledge Bank (EKB), started from 01 January 2022, and my institute (Tanta University) is one of the participating institutes.
Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Data Availability Please contact the authors for data requests.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests All of the authors confirm that there are no conflicts of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

Ahmed DA, Slima DF, Al-Yasi HM, Hassan LM, Galal TM (2023) Risk assessment of trace metals in *Solanum lycopersicum* L. (tomato) grown under wastewater irrigation conditions. Environ Sci Pollut Res 30:42255–42266. https://doi.org/10.1007/s11356-023-25157-8

Ajayi TO, Ogunbayo AO (2012) Achieving environmental sustainability in wastewater treatment by phytoremediation with water hyacinth (*Eichhornia crassipes*). J Sustain Dev 5:80

Akhtar N, Ahmad K, Hameed M, Nawaz F, Hamid A, Segovia-Salcedo M, Shahnaz M (2017) Leaf anatomical and biochemical adaptations in *Typha domingensis* Pers. Ecotypes for salinity tolerance. Bot Sci 95(4):807–821. https://doi.org/10.17129/botsci.886

Akhter N, Aqeel M, Shahnaz M, Alnusairi G, Alghanem S, Kausar A, Hashem M, Kanwal D, Alamri S, Ilyas A, Al zoubi O, Noman A (2021) Physiological homeostasis for ecological success of *Typha* (*Typha domingensis* Pers.) Populations in saline soils. Physiol Mol Biol Plants 27:687–701. https://doi.org/10.1007/s12298-021-00963-x

Ali H, Khan E, Sajad MA (2013) Phytoremediation of heavy metal concepts and applications. Chemosphere 91:869–881. https://doi.org/10.1016/j.chemosphere.2013.01.075

Allen SE (1989) Chemical analysis of ecological materials. Blackwell Scientific, London

APHA, AWWA, WEF (American Public Health Association, American Water Works Association and Water Environment Federation) (2005) Standard methods for the examination of water and wastewater. American Public Health Association, Washington

Awad HEA, Mohammad AM, Farahat EA (2023) Potential use of dry powder of Vossia cuspidata (Roxb.) Griff. Rhizomes and leaves in methylene blue dye remediation. Sci Rep 13:11073. https://doi.org/10.1038/s41598-023-37987-0

Badr N, Fawzy M, Al-Qahtani KH (2012) Phytoremediation: an ecological solution to heavy metals polluted soil and evaluation of plant removal ability. World Appl Sci J 16:1292–1301

Balkhair KS, AshrafMA (2016) Field accumulation risks of heavy metals in a soil and vegetable crop irrigated with sewage water in western region of Saudi Arabia. Saudi J Biol Sci 23:32–44. https://doi.org/10.1016/j.sjbs.2015.09.023

Barbosa B, Boléo S, Sidella S, Costa J, Duarte MP, Mendes B, Cosentino SL, Fernando AL (2015) Phytoremediation of heavy metal-contaminated soils using the perennial energy crops *Miscanthus* spp. and *Arundo donax* L. Bioenergy Res 8:1500–1511. https://doi.org/10.1007/s12155-015-9688-9

Batool R, Hameed M, Ashraf M, Fatima S, Nawaz T, Ahmad MSA (2014) Structural and functional response tometal toxicity in aquatic *Cyperus alopecuroides* Rottb. Limnolog 48:46–56. https://doi.org/10.1016/j.limno.2014.06.002

Bello AO, Tawabini BS, Khalil AB, Boland CR, Saleh TA (2018) Phytoremediation of cadmium-, lead- and nickel-contaminated

water by *Phragmites australis* in hydroponic systems. Ecol Eng 120:126–133. https://doi.org/10.1016/j.ecoleng.2018.05.035

Benson NU, Anake WU, Olanrewaju IO (2013) Analytical relevance of trace metal speciation in environmental and bio physicochemical systems. Am J Anal Chem 4:633–641. https://doi.org/10.4236/ajac.2013.411075

Benson NU, Anake WU, Essein JP, Olajire AA (2016) Distribution and risk assessment of trace metals in *Leptodius exatrata* surface water and sediments from Douglas Creek in the Qua Iboe Estuary. Integrat Medic Res 11(3):434–449. https://doi.org/10.1016/j.jtusci.2016.08.004

Bonanno G, Lo Giudice R (2010) Heavy metals bioaccumulation by the organs of *Phragmites australis* (common reed) and their potential use as contamination indicators. Ecol Indicat 10:639–645. https://doi.org/10.1016/j.ecolind.2009.11.002

Bonanno G, Borg JA, Di Martino V (2017) Levels of heavy metals in wetland and marine vascular plants and their biomonitoring potential: a comparative assessment. Sci Total Environ 576:796–806. https://doi.org/10.1016/j.scitotenv.2016.10.171

Boulos L (2005) Flora of Egypt, Monocotyledones (Alismataceae-Orchifaceae). Al Hadara Publishing, Cairo, Egypt, Egypt

Chen L, Liu F, Wang Y, Li X, Zhang S, Li Y, Wu J (2015) Nitrogen removal in an ecological ditch receiving agricultural drainage in subtropical central China. Ecol Eng 82:487–492. https://doi.org/10.1016/j.ecoleng.2015.05.012

Chiroma TM, Ebewele RO, Hymore FK (2014) Comparative assessment of heavy metal levels in soil, vegetables and urban grey wastewater used for irrigation in Yola and Kano. Int Ref J Eng Sci 3:01–09

Cristaldi A, Conti GO, Cosentino SL, Mauromicale G, Copat C, Grasso A, Zuccarello P, Fiore M, Restuccia C, Ferrante M (2020) Phytoremediation potential of *Arundo donax* (Giant Reed) in contaminated soil by heavy metals. Environ Res 185:109427

Da Cunha Cruz Y, Martins Scarpa AL, Pereira MP, Mauro de Castro E, Pereira FJ (2020) Root anatomy and nutrient uptake of the cattail *Typha domingensis* Pers. (Typhaceae) grown under drought condition. Rhizosphere 16:100253. https://doi.org/10.1016/j.rhisph.2020.100253

Dhir B (2013) Phytoremediation: role of aquatic plants in environmental clean-up. Springer, New Delhi, p 111

Diagne N, Ngom M, Djighaly PI, Ngom D, Ndour B, Cissoko M, Faye M, Sarr A, Sy MO, Laplaze L, Champion A (2015) Heavy metal contamination of soils: monitoring and remediation. In: Sherameti I, Varma A (eds) Heavy metal contamination of soils monitoring and remediation. Springer International Publishing Switzerland

Dökmeci A (2020) Environmental Impacts of heavy metals and their Bioremediation

Eid EM, Shaltout KH, El-Sheikh MA, Asaeda T (2012a) Seasonal courses of nutrients and heavy metals in water, sediment and above- and below-ground *Typha domingensis* biomass in Lake Burullus (Egypt): perspective for phytoremediation. Flora 207:783–794. https://doi.org/10.1016/j.flora.2012.09.003

Eid E, El-Sheikh M, Alatar A (2012b) Uptake of Ag, Co and Ni by the Organs of *Typha domingensis* (Pers.) Poir. ex Steud. in Lake Burullus and Their Potential Use As Contamination Indicators. Open Journal of Modern Hydrology 2: 21–27. https://doi.org/10.4236/ojmh.2012.21004

Eid EM, Youssef MSG, Shaltout KH (2016) Population characteristics of giant reed (*Arundo donax* L.) in cultivated and naturalized habitats. Aquat Bot 129:1–8. https://doi.org/10.1016/j.aquabot.2015.11.001

Eid EM, Shaltout KH, Moghanm FS, Youssef MS, El-Mohsnawy E, Haroun SA (2019) Bioaccumulation and translocation of nine heavy metals by *Eichhornia crassipes* in Nile Delta, Egypt: perspectives for phytoremediation. Int J Phytoremediat 21:821–830. https://doi.org/10.1016/j.flora.2012.09.003

Eid EM, Shaltout KH, Al-Sodany YM, Haroun SA, Galal TM, Ayed H, Khedher KM, Jensen K (2020a) Common reed (*Phragmites australis* (Cav.) Trin. ex Steudel) as a candidate for predicting heavy metal contamination in Lake Burullus, Egypt: a biomonitoring approach. Ecol Eng 148:105787. https://doi.org/10.1016/j.ecoleng.2020.105787

Eid EM, Galal TM, Shaltout KH, El-Sheikh MA, Asaeda T, Alatar AA, Alfarhan AH, Alharthi A, Alshehri AM, Picó Y, Barcelo D (2020b) Biomonitoring potential of the native aquatic plant *Typha domingensis* by predicting trace metals accumulation in the Egyptian Lake Burullus. Sci Total Environ 714:136603. https://doi.org/10.1016/j.scitotenv.2020.136603

El-Shamy M, Heikal Y, Bonanomi G (2019) Phytoremediation efficiency of *Portulaca oleracea* L. naturally growing in some industrial sites, Dakahlia district, Egypt. https://doi.org/10.1016/j.chemosphere.2019.03.099. Chemosphere 225

Eltaher GT, Ahmed DA, El-Beheiry M, Sharaf El-Din A (2019) Biomass estimation and heavy metal accumulation by *Pluchea Dioscoridis* (L.) DC. In the Middle Nile Delta, (Egypt): perspectives for phytoremediation. S Afr J Bot 127:153–166. https://doi.org/10.1016/j.sajb.2019.08.053

Farahat EA, Galal TM (2018) Trace metal accumulation by *Ranunculus sceleratus*: implications for phytostabilization. Environ Sci poll Res 25:4214–4222. https://doi.org/10.53771/ijbpsa.2022.3.1.0032

Farahat EA, Mahmoud WF, Awad HEA, Farrag HF, Arshad M, Eid EM, Fahmy GM (2021) Prediction models for evaluating the Uptake of Heavy metals by the Invasive Grass Vossia cuspidata (Roxb.) Griff. In the River Nile, Egypt: a Biomonitoring Approach. Sustainability 13:10558. https://doi.org/10.3390/su131910558

Galal TM, Shehata HS (2016) Growth and nutrient accumulation potentials of giant reed (*Arundo donax* L.) in different habitats in Egypt. Int J Phytoremed 18:1221–1230. https://doi.org/10.1080/15226514.2016.1193470

Galal TM, Gharib FA, Ghazi SM, Mansour KH (2017a) Phytostabilization of heavy metals by the emergent macrophyte *Vossia cuspidata* (Roxb.) Griff.: a phytoremediation approach. Int J Phytoremed 19:992–999. https://doi.org/10.1080/15226514.2017.1303816

Galal TM, Gharib FA, Ghazi SM, Mansour KH (2017b) Metal uptake capability of *Cyperus articulatus* L. and its role in mitigating heavy metals from contaminated wetlands. Environ Sci Pollut Res 24:21636–21648. https://doi.org/10.1007/s11356-017-9793-8

Galal TM, Eid EM, Dakhil MA, Hassan LM (2018) Bioaccumulation and rhizofiltration potential of *Pistia stratiotes* L. for mitigating water pollution in the Egyptian wetlands. Int J Phytoremed 20:440–447. https://doi.org/10.1080/15226514.2017.1365343

Galal TM, Al-Sodany YM, Al-Yasi HM (2019) Phytostabilization as a phytoremediation strategy for mitigating water pollutants by the floating macrophyte *Ludwigia Stolonifera* (Guill. Int J Phytoremed 4:373–382. https://doi.org/10.1080/15226514.2019.1663487. Perr.) P.H. Raven

Galal TM, Shedeed ZA, Gharib FA, Al-Yasi HM, Mansour KH (2021) The role of *Cyperus alopecuroides* Rottb. Sedge in monitoring water pollution in contaminated wetlands in Egypt: a phytoremediation approach. Environ Sci Pollut Res 28:23005–23016. https://doi.org/10.1007/s11356-020-12308-4

Galal T, Gharib F, Al-Yasi H, Al-Mutairi K, Mansour K, Eid E (2022) Nutrient remediation efficiency of the sedge plant (*Cyperus alopecuroides* Rottb.) To restore Eutrophic Freshwater ecosystems. Sustainability 14:2823. https://doi.org/10.3390/su14052823

Gharib FA, Mansour KH, Ahmed EZ, Galal TM (2020) Heavy metals concentration, and antioxidant activity of the essential oil of the wild mint (*Mentha longifolia* L.) in the Egyptian watercourses. Int J Phytoremed 23:641–651

Ghazi SM, Galal TM, Hussein KM (2019) Monitoring Water Pollution in the Egyptian watercourses: a Phytoremediation Approach. LAP LAMBERT Academic Publishing, Saarbrücken

Gomes MVT, De Souza RR, Teles VS, Mendes EA (2014) Phytoremediation of water contaminated with mercury using *Typha domingensis* in constructed wetland. Chemosphere 103:228–233. https://doi.org/10.1016/j.chemosphere.2013.11.071

Guo G, Xiao J, Jeong BR (2022) Iron source and medium pH affect nutrient uptake and pigment content in Petunia hybrida 'Madness red' cultured in Vitro. Int J Mol Sci 23:8943. https://doi.org/10.3390/ijms23168943

Hadad H, Mufarrege M, Pinciroli M, Di Luca G, Maine M (2010) Morphological response of *Typha domingensis* to an Industrial Effluent containing heavy metals in a constructed Wetland. Arch Environ Contam Toxicol 58:666–675. https://doi.org/10.1007/s00244-009-9454-0

Hegazy AK, Abdel-Ghani NT, El-Chaghaby GA (2011) Phytoremediation of industrial wastewater potentiality by *Typha domingensis*. Int J Environ Sci Technol 8:639–648. https://doi.org/10.1007/BF03326249

Hellal F, El-Sayed S, Zewainy R, Amer A (2019) Importance of phosphate pock application for sustaining agricultural production in Egypt. Bull Natl Res Cent 43:11. https://doi.org/10.1186/s42269-019-0050-9

Ievinsh G, Landorfa-Svalbe Z, Andersone-Ozola U, Karlsons A, Osvalde A (2022) Salinity and Heavy Metal Tolerance, and Phytoextraction potential of Ranunculus sceleratus plants from a Sandy Coastal Beach. Life (Basel) 12:1959. https://doi.org/10.3390/life12121959

Karunaratne S, Asaeda T, Yutani K (2003) Growth performance of *Phragmites australis* in Japan: influence of geographic gradient. Environ Exp Bot 50:51–66. https://doi.org/10.1016/S0098-8472(02)00114-4

Lu RK (2000) Methods of inorganic pollutants analysis. Soil and agrochemical analysis methods. Agricultural Science and Technology, Beijing

Manios T, Stentiford EI, Millner PA (2003) The effect of heavy metals accumulation on the chlorophyll concentration of *Typha latifolia* plants, growing in a substrate containing sewage sludge compost and watered with metalliferous water. Ecol Eng 20:65–74. https://doi.org/10.1016/S0925-8574(03)00004-1

Moussa SA (2015) Heavy metal Acquisition from Drain Water, Sediment and Soil by two species of amphibious plants. Egypt J Bot 55:105–125

Mufarrege MM, Hadad HR, Di Luca GA, Maine MA (2014) Metal dynamics and tolerance of *Typha domingensis* exposed to high concentrations of Cr, Ni and Zn. 105:90–96. https://doi.org/10.1016/j.ecoenv.2014.04.008. Ecotoxicol Environ Saf

Næsted H, Holm A, Jenkins T, Nielsen HB, Harris CA, Beale MH, Andersen M, Mant A, Scheller H, Camara B (2004) Arabidopsis variegated 3 encodes a chloroplast-targeted, zinc-finger protein required for chloroplast and palisade cell development. J Cell Sci 117:4807–4818. https://doi.org/10.1242/jcs.01360

Nagajyoti PC, Lee KD, Sreekanth TVM (2010) Heavy metals, occurrence and toxicity for plants: a review. Environ Chem Lett 8:199–216. https://doi.org/10.1007/s10311-010-0297-8

Norah MM (2014) Impact of copper mining stockpiles on diversity of plants, soils, and *Cyperus papyrus* of Kahendero swamp, Lake George, Uganda. J Dermatol Sci 4:195–205

Odjegba VJ, Fasidi IO (2007) Phytoremediation of heavy metals by *Eichhornia crassipes*. Environmentalist 27:349–355

Oves M, Mohammad K, Almas Z, Ees A (2012) Soil Contamination, Nutritive Value, and Human Health Risk Assessment of heavy metals: An Overview. In: Zaidi (eds.) Toxic Metals Legumes Bioremediation 1–28. https://doi.org/10.1007/978-3-7091-0730-0_1

Pletsch M (2003) Plant and the environment phytoremediation. In: Thomas B (ed) Encyclopedia of Applied Plant sciences. Elsevier, Oxford, pp 781–786

Rezania S, Park J, Rupani PF, Darajeh N, Xu X (2019) Phytoremediation potential and control of *Phragmites australis* as a green phytomass: an overview. Environ Sci Pollut Res 26:7428–7441. https://doi.org/10.1007/s11356-019-04300-4

Rowell DL (1994) Soil science: methods and applications. Addison Wesley Longman Singapore Publishers (Pte) Ltd, England, UK, p 350

Salt D, Blaylock M, Kumar N, Dushenkov V, Ensley B, Chet I, Raskin I (1995) Phytoremediation: a Novel Strategy for the removal of toxic metals from the Environment using plants. Bio/technology. (Nature Publishing Company) 13:468–474

Sarwar N, Imran M, Shaheen MR, Ishaq W, Kamran A, Matloob A, Rehim A, Hussain S (2017) Phytoremediation strategies for soils contaminated with heavy metals: modifications and future perspectives. Chemosphere 171:710–721. https://doi.org/10.1016/j.chemosphere.2016.12.116

Sellal A, Belattar R, Bouzidi A (2019) Trace elements removal ability and antioxidant activity of *Phragmites australis* (from Algeria). Int J Phytoremed 21:456–460. https://doi.org/10.1080/15226514.2018.1537252

Shaltout KH, Galal TM, El-Komy TM (2010) Evaluation of the nutrient status of some hydrophytes in the water courses of Nile Delta, Egypt. Ecologia Mediterranea 36:77–87

Shaltout KH, Galal TM, El-Komy TM (2013) Biomass, nutrients and nutritive value of *Persicaria Salicifolia* Willd. In the water courses of Nile Delta, Egypt. Rend Fis Acc Lincei 25:167–179. https://doi.org/10.1007/s12210-013-0269-6

Sharma P, Asaeda T, Manatunge J, Fujino T (2006) Nutrient cycling in a natural stand of *Typha angustifolia*. J Freshw Ecol 21:431–438. https://doi.org/10.1080/02705060.2006.9665020

Slima DF, Ahmed DA (2020) Trace metals accumulated in pea plant (*Pisum sativum* L.) as result of Irrigation with Wastewater. J Soil Sci Plant Nut 20:2749–2760. https://doi.org/10.1007/s42729-020-00341-8

Soner M, Uyanik A, Cay S (2017) Investigation of trace metals distribution in water, sediments and wetland plants of Kızılırmak Delta, Turkey. Int J Sed Res 32(1):90–97. https://doi.org/10.1016/j.ijsrc.2016.03.004

SPSS (2012) IBM SPSS statistics version 21.0. Copyright of IBM and other(s) 1989–2012, USA

Tabinda AB, Irfan R, Yasar A, Iqbal A, Mahmood A (2020) Phytoremediation potential of *Pistia stratiotes* and *Eichhornia crassipes* to remove chromium and copper. Environ Technol 1–7

Weis JS, Weis P (2004) Metal uptake, transport and release by wetland plants: implications for phytoremediation and restoration. Environ Int 30:685–700. https://doi.org/10.1016/j.envint.2003.11.002

Zhang JT, Xi Y, Li J (2006) The relationships between environment and plant communities in the middle part of Taihang Mountain Range, North China. Commun Ecol 7:155–163. https://doi.org/10.1556/ComEc.7.2006.2.3

Zhao Y, Xia X, Yang Z (2013) Growth and nutrient accumulation of *Phragmites australis* in relation to water level variation and nutrient loadings in a shallow lake. J Environ Sci 25:16–15. https://doi.org/10.1016/S1001-0742(12)60004-7

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.