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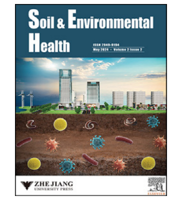

Full Article

Metal and nutrient uptake by natural wetland plants in a tropical man-made wetland of Sri Lanka

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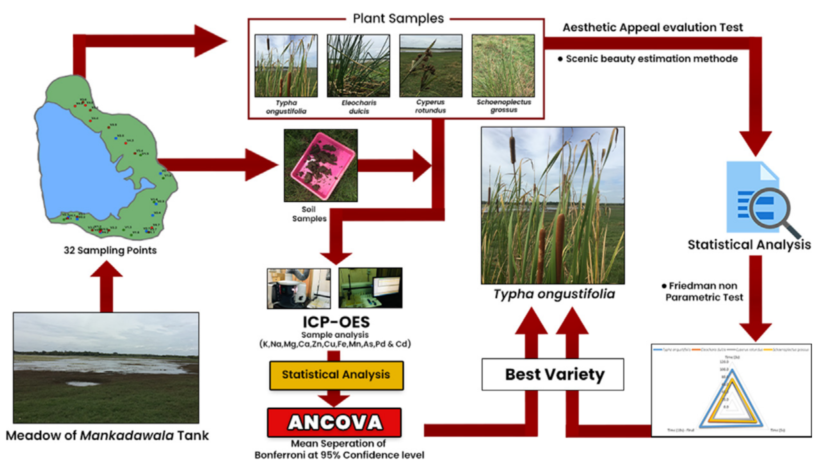
HIGHLIGHTS

- Metal and nutrient uptake ability of four naturally grown aquatic plants were evaluated
- Wetland plants were taken from a man-made wetland belonging to a small reservoir
- The aquatic plants are potential hyper-accumulators for N, P, and K
- *Typha angustifolia*, with its high aesthetic appeal, was selected as the preferred plant species

GRAPHICAL ABSTRACT



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ABSTRACT

Phytoremediation of contaminated soil is an environmentally-friendly approach to minimize the impacts of nutrients and heavy metals on an ecosystem. Hence, selecting appropriate plants with phytoextraction potential is paramount to remediate contaminated soils. This study aimed to investigate the nutrient and metal contents of four natural aquatic plants, including *Cyperus rotundus*, *Eleocharis dulcis*, *Typha angustifolia*, and *Schoenoplectus grossus*. They were grown in the meadow of a small reservoir in Sri Lanka to assess their phytoextraction ability using plant and soil samples collected at 32 sampling points in the meadow. Their biological concentration (roots/soil), accumulation (shoots/soil), and translocation (shoots/roots) factors were determined to assess element mobility and phytoextraction ability. Total K, Na, Mg, Ca, Zn, Cu, Fe, Mn, As, Pb, and Cd contents of plants and soil samples were measured using an Inductivity Couple Plasma Optical Emission Spectrophotometer. ANCOVA was used as a statistical test to assess the best plant type in terms of nutrient and metal absorption. Plant shoots exhibited significantly greater values for P, Na, Mg, Zn, Cd, and Fe than their roots. Their biological concentration, accumulation and translocation factors were not different among the four plant species. However, these values were >1 for all the species, indicating their potential to be used as hyperaccumulators. *T. angustifolia*, with its high potential for nutrient and metal accumulation and the highest aesthetic appeal, was selected as the best overall wetland species for phytoremediation purposes.

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1. Introduction

Intensive agriculture, unregulated industrial growth, and urbanization have increased the abundance of plant nutrients, heavy metals, and other pollutants that cause environmental pollution (Briffa et al., 2020; Ruas et al., 2022). Farmers commonly apply excess manure, synthetic fertilizers, and other agro-chemicals to improve agricultural production without considering the recommended doses. This can lead to offsite transport and leaching of nutrients, heavy metals, and other pollutants, which can contaminate soils and surface, subsurface, and ground waters (Jaja et al., 2023).

The dry and intermediate zones of Sri Lanka are the food basket for the country Villholth and Rajasooriyar (2010). The use of agrochemicals for crop production is the primary means of pest management, and synthetic fertilizer remains the primary source of crop nutrients in Sri Lanka (Dandeniya and Caussi, 2020; Abeysingha et al., 2020). Sub-optimal use efficiency of fertilizers, such as nitrogen and phosphorus, is common and the resultant runoff often harms the environment (Jayasiri et al., 2022). It is reported that the excessive presence of nutrients and agro-chemicals in the low-lying areas and water bodies in the dry and intermediate zones of Sri Lanka has caused severe environmental problems (Sanjeevani et al., 2013; Abeysingha et al., 2016, 2021; Jayasiri et al., 2022).

Phytoremediation, the utilization of plants and their symbiotic microorganisms for environmental restoration is widely considered a cost-effective and non-invasive alternative to engineering-driven remediation approaches (Khalid et al., 2017). Plants can accomplish pollutant stabilization, extraction, degradation, and volatilization, making them versatile agents for addressing several environmental contaminants (Wang and Delavar, 2024). These numerous phytoremediation technologies are well understood, and their suitability for various organic and inorganic pollutants remediation is documented (Kochi et al., 2020). Phytoremediation holds six main strategies including phytoaccumulation/phytoextraction, phytotransformation, phytostabilization, phytovolatilization, phytostimulation, and rhizofiltration (Woraharn et al., 2021). Depending upon the contaminants and the environment, plants use one or more of these mechanisms to reduce pollutant concentrations from soil and water. It is reported that contaminated groundwater can be remediated through rhizo-filtration, phytovolatilization, rhizo-degradation and phytodegradation (Kafle et al., 2022). Soil, sediments, and sludge contaminants are remediated through phytoextraction, phytodegradations, phytostabilization, rhizodegradation or phytovolatilization, whereas surface and wastewater contaminations can be treated by rhizofiltration, phytodegradation or rhizodegradation (Kafle et al., 2022).

Interest in preserving and restoring native plant communities with remedial capabilities is emerging, driven by the recognition of native plants' economic, ecological, genetic, and aesthetic advantages and a growing societal appreciation for their inherent value as living organisms (Dorner, 2002). Rajakaruna et al. (2006) reported the presence of metal hyper-accumulating plants in Sri Lanka. One of these species, *Rinorea benghalensis*, is known to hyperaccumulate Ni, with up to 1% Ni by dry weight extracted from a herbarium specimen. Therefore, investigating the locally grown plant varieties for pollutant remediation is vital. However, plant species suitable for phytoremediation need to be hardy in nature, high in biomass, and tolerant to the toxic effects of metals and contaminants. In addition, they should be easy to cultivate, have high absorption capacity, and be resistant to herbivory (Sakakibara et al., 2011; Shabani and Sayadi, 2012). Plant varieties which were studied in the present study (*Cyperus rotundus*, *Eleocharis dulcis*, *Typha angustifolia*, *Schoenoplectus grossus*) occurred naturally in a special man-made wetland.

The Tank Cascade System (TCS) in Sri Lanka is a special watershed within which a series of tanks (small reservoirs) are constructed along the hydrologic flow path (Abeysingha et al., 2021). In this system, irrigation

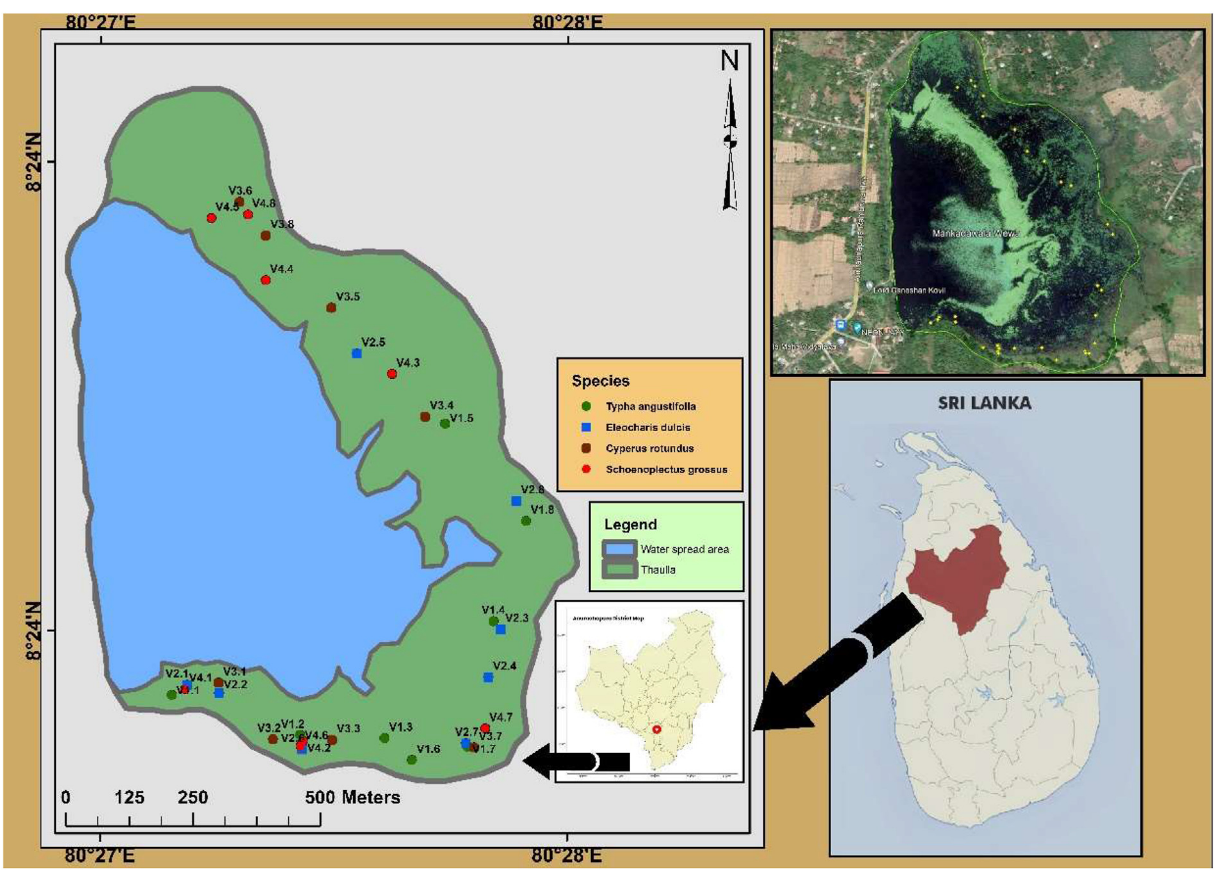

Fig. 1. Geographical location of the Mankadawala small reservoir (tank) and sampling points of four aquatic plants.

water from the upper tank is drained into the next downstream tank, and spilled water from the upper tank is captured by the next downstream tank. This water flows towards the water spread area of the tank through a special man-made wetland area referred to as Thaulla area, a kind of meadow (Abeysingha et al., 2018). Thaulla is a wetland habitat with diverse flora and fauna (Kotagama and Bambaradeniya, 2006). Due to the availability of higher nutrient concentrations, there is a high productivity among plant species. The massive root structure of these plants, as well as their plant biomass, trap sediments, nutrients, and contaminants flowing with water. In the absence of a Thaulla community, contaminated water may flow directly into the tank's water collecting area, posing a risk to water users. Gunapala and Abeysingha (2019) showed that there is an accumulation of nutrients and heavy metals in the Thaulla area, taking Ulankulama tank as a case study. Most of these nutrients and other contaminants are thought to be absorbed by the plants that grow naturally in the Thaulla area. Sedges and grasses are common components of meadows or Thaulla areas.

With this background, the objective of this study was to identify the nutrient and metal uptake capabilities of aquatic plants naturally growing in the Thaulla area of the Mankadawala tank. We sought to select the best plant variety based on its nutrient and heavy metal accumulation capability and aesthetic appeal to introduce to other tank systems, as well as to introduce it to constructed wetlands for wastewater treatment.

2. Materials and methods

2.1. Study site and sampling procedure

The Mankadawala small reservoir (tank) in Pandulagama Divisional Secretariat Division of Anuradhapura District, North Central Province, served as the site for the field study. It is situated next to the Anuradhapura - Jaffna road, about 12.8 km northeast of Anuradhapura city. Farmers use the water from the Mankadawala tank to irrigate a 1,052,184 m^2 command area. Geographical location of the Mankadawala tank and its Thaulla area is shown in Fig. 1, and Thaulla occupies about 470,000 m^2 of this area.

The entire Thaulla area was observed to contain naturally growing sedges and other plants, and four plant varieties were considered as abundant. Each of the dominant plants species were sent to the National Herbarium, Peradeniya, Sri Lanka, for identification as *T. angustifolia*, *E. dulcis*, *C. rotundus*, and *S. grossus*. These four plant types were sampled as representative of the entire Thaulla area. Whole plants were uprooted from the sample points, and the latitude and longitude of the points were recorded. The main branches of mature, well-grown plants that received sufficient sunshine below the growing tips were chosen for the plant sample. Soil samples were collected from the root zone depth (0–20 cm) at the same location where plants were removed. Based on the abundance of plant types, eight plants (replicates) were collected for each of the four plant species. These soil and vegetation samples were put into labeled, pre-cleaned polythene bags separately and sent to the laboratory for nutrient and metal analyses. All plants were collected during the dry season (July/2022).

2.2. Four aquatic plants

C. rotundus belongs to the family Cyperaceae and grows as a perennial plant close to water resources. It can be found in a wide range of agro-climatic zones and is common in temperate, tropical, and subtropical regions, such as South, Southeast East and Central Asia, Africa, South and North America, and Australia (Dhar et al., 2017). It is an erect, perennial sedge that reaches a height of 7 to 40 cm. *C. rotundus* is considered a potential hyperaccumulator plant though it is a weed in agricultural fields (Dhar et al., 2017).

E. dulcis is included in the family Cyperaceae. This plant is commonly found in lakes or waterlogged areas. The stem of this plant is cylindrical or obtuse square and 2 to 3 mm in diameter with a plant height of up to 150 cm. This plant is unbranched and green with flowers found at the end of the stems. Several studies show that this plant can be used as a hyperaccumulator in constructed wetlands systems (Santosa et al., 2021).

T. angustifolia belongs to the Typhaceae family and is an erect, perennial freshwater aquatic herb that can grow three or more meters tall. The leaves are thick, ribbon-like structures with a spongy cross-section exhibiting air channels. *T. angustifolia* can be found in wetlands, sedge meadows, along slow-moving streams, river banks, and lake shores. The plant can be observed in areas of widely fluctuating water levels, such as roadside ditches, reservoirs and other disturbed wet soil areas (Demırezen and Aksoy, 2004).

S. grossus belongs to the family Cyperaceae. It is commonly found in fresh-water swamps, edges of ponds, and moist soils. Plants are stoloniferous with the roots of *S. grossus* being fibrous and spread out horizontally in the soil to anchor the plant and absorb water and nutrients (Flora of China, 2013).

2.3. Sample pre-preparation and analysis

Individual plant samples were thoroughly cleaned with running water in the lab to avoid any surface contamination before being rinsed with distilled water to remove any remaining impurities. Then, plant samples were separated into roots and shoots, dried by air for two to three days, and then dried in an oven at 60 °C for 1–2 days. Plant samples were ground in an agate mortar to establish a uniform element distribution in the powder.

All soil samples were air dried in an environment that avoided cross-contamination between samples or with outside materials. Soil aggregates were crushed and the samples dried, followed by removal of stone fragments and plant roots. Then, a hammer was used to grind the soil samples to pass a 2-mm sieve. The air dried and sieved soil samples were labeled and stored in clean polythene bags for subsequent analyses. Concentrations of total N, P, K, Na, Mg, Ca, and heavy metals such as Zn, Cu, Fe, Mn, As, Pb, and Cd were determined for soil and plant samples. The soil samples were further examined for pH, EC, and moisture content.

Soil pH was determined by pHep + pH Tester (HANNA, HI98108) using a 1:2.5 soil:water suspension (Rowell, 1994). Soil EC was determined with a EC/TDS/Temperature Tester (HANNA, HI98311) using the 1:5 soil:water suspension (Chapman and Pratt, 1961). Total N content of soil samples was determined using the Kjeldahl procedure (Heating Digester - DK 20, Semi-Automatic Distillation Unit - UDK 132) (Bremner and Mulvaney, 1982) with the wet oxidation technique (hydrogen peroxide 30%, lithium sulphate, selenium powder, sulphuric acid, ~36 N). Total P in soil was measured by wet oxidation using the Murphy and Riley colorimetric method (UV-VIS Double Beam Spectrophotometer - UVD2960) (Akinremi et al., 2003). Total K, Na, Mg, Ca, Zn, Cu, Fe, Mn, As, Pb, and Cd contents were measured using an Inductivity Couple Plasma Optical Emission Spectrophotometer (ICP-OES) (iCAP 7000) after acid digestion of soil samples (Seras, 2006).

Total nitrogen content of plant samples was measured by the semi-micro Kjeldahl method (Heating Digester - DK 20, Semi-Automatic Distillation Unit - UDK 132) using a wet oxidation technique (Tandon, 1999). Total phosphorous content of plant samples was measured by dry ashing followed by the Murphy and Riley colorimetric method (UV-VIS Double Beam Spectrophotometer- UVD2960) (Seras, 2006). Total K, Na, Mg, Ca, Zn, Cu, Fe, Mn, As, Pb, and Cd contents in plant samples were measured using the ICP-OES (iCAP 7000) procedure after dry ashing of plant samples (Seras, 2006).

Quality control was conducted to minimize the matrix effects using blank samples for both soil and plant analyses. Authenticated samples were used for the confirmation data for quality control and quality assurance. The limit of quantitation was ppm for alkaline metals, alkaline earth metals, and trace metals, while ppb was for heavy metals such as As, Pb and Cd.

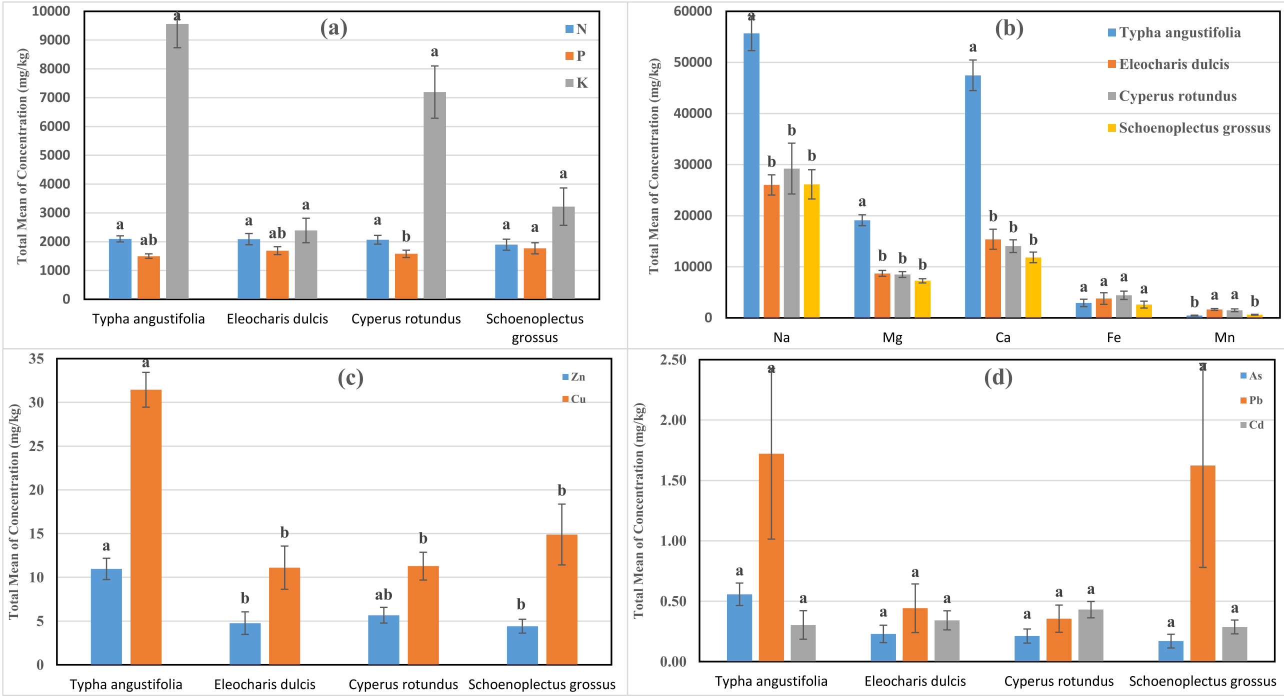

Fig. 2. Nutrients and metal contents in the biomass of four aquatic species.

Biological concentration (BCF), biological accumulation (BAF) and translocation (BTF) factors were determined to assess element mobility and phytoextraction ability of the studied species based on the following equations (Yoon et al., 2006; Agarwal et al., 2022):

$$BCF = \frac{Metal\ concentration\ in\ roots}{Metal\ concentration\ in\ soil} \quad \text{Eq. 1}$$

$$BAF = \frac{Metal\ concentration\ in\ shoots}{Metal\ concentration\ in\ soil} \quad \text{Eq. 2}$$

$$BTF = \frac{Metal\ concentration\ in\ shoots}{Metal\ concentration\ in\ roots} \quad \text{Eq. 3}$$

The visual attractiveness of plants growing in the Thaulla area was assessed using a systematic approach that includes study area overview, sample selection and acquisition, evaluators, and a scenic beauty estimation (SBE) method (Tan et al., 2021). SBE was conducted using 32 panelists with an aesthetic attitude and sensibility (Tan et al., 2021).

2.4. Statistical analysis

ANCOVA, with a mean separation of Bonferroni at a 95% confidence level, was used as a statistical test to assess the best plant type in terms of nutrient and heavy metal absorption. Moreover, the same analysis was performed to evaluate the differences in soil parameters associated with each plant sample. ANOVA with LSD mean separation ($p < 0.05$) was used to compare the differences in nutrient and heavy metal concentrations between roots and shoots of plants, and the same test was conducted to assess significant differences among the four plant species in terms of BAF, BTF, and BCF considering nutrients and metals.

Aesthetic appeal evaluation was conducted using 32 panelists with an aesthetic attitude and sensibility in 21 days after sampling by showing images of the individual plants one at a time and showing the next images after 3, 5, and 10-s time gaps. A five-point hedonic scale (Excellent 8–10, Good 6–8, Medium 4–6, General 2–4, Poor 0–2) was used to estimate the aesthetic preference (Tan et al., 2021). These data were analyzed using the Friedman non-parametric method in MINITAB 16 software with a 95% confidence interval to assess significant differences in species aesthetic preference.

3. Results and discussions

3.1. Variation of nutrient and metal contents in plant biomass

N, P, and K are considered major nutrients for plant growth and development. However, offsite transport and contamination of these nutrients in surface and groundwater lead to eutrophication of water-bodies. There is a potential of Mankadawala tanks to be contaminated due to runoff from paddy growing areas. Therefore, if sedges are grown in the meadow (Thaulla area) the excess nutrients can be removed reducing the risk of eutrophication. Fig. 2 shows the mean values of nutrient and metal contents in whole plants of the four species and their statistical relationships assessed by ANCOVA. Potassium is the nutrient recorded in the highest quantities of all four plants (Fig. 2a). The observed values for the total K (mg/kg) varied from 2389 to 9561 mg/kg and were not significantly different (p $>$ 0.05) among the plant species (Fig. 2).

The observed values for total N (mg/kg of dry weight) of the four plant types varied from 1895 to 2099 mg/kg. Comparing the four plant varieties in the Thaulla area, the total N (mg/kg) value was not significantly different ($p > 0.05$) (Fig. 2a). The critical level of N in many plants is 10,000–30,000 mg/kg. These values can differ depending on the soil nutrient content, environmental factors and available form of minerals (Rydén et al., 2008). Normally, Sri Lanka being a tropical country, N values in plants are less than 10,000 mg/kg (Rydén et al., 2008). The total phosphorous (mg/kg) value of the four plant types in the Thaulla area ranged from 1500 to 1771 mg/kg. Comparing the four sedges, *S. grossus* demonstrated a greater ($p < 0.05$) P value than the others, indicating that *S. grossus* has a higher affinity for P (Fig. 2a). In tropical wetland systems, the removal of phosphorous is significant rather than nitrogen through plant uptake (Yousaf et al., 2021).

Considering the remaining elements, significant differences were observed in Na, Mg, Ca, Zn, Cu, and Mn. *T. angustifolia* in the Thaulla area

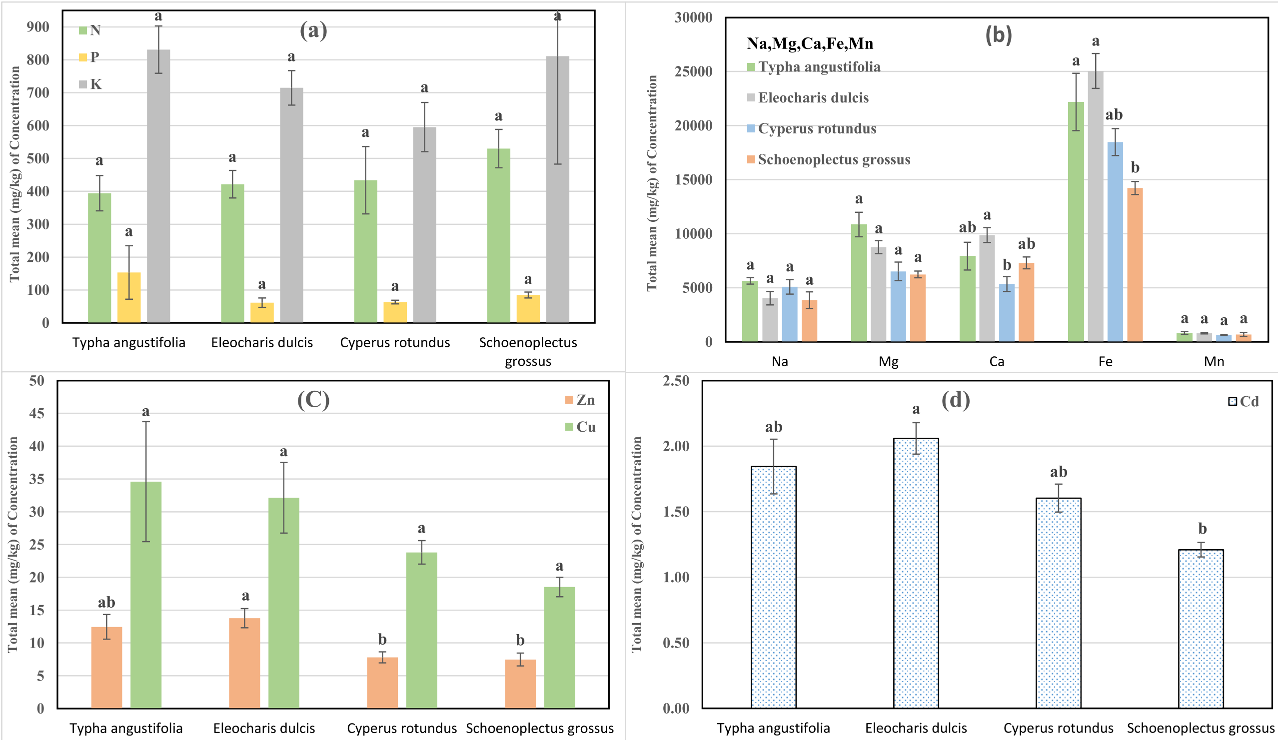

Fig. 3. Nutrient and other metal contents in the rhizosphere soil under four aquatic species.

demonstrated greater values ($p < 0.05$) for Na, Mg, Ca, Zn and Cu than those of the other tested plant types (Fig. 2). *E. dulcis* and *C. rotundus* in the Thaulla area showed a greater value ($p < 0.05$) for Mn than the other two species (Fig. 2). Considering As, Pb, and Cd concentrations in four plant types, low concentrations are recorded and are not significantly different among the plant types. According to a previous study (Subhasini and Swamy 2014), the whole plant of the *C. rotundus* accumulated 16.4 mg/kg of Cd within 60 days, indicating that *C. rotundus* has good potential as a Cd accumulator. Since there are no considerable quantities of soil Cd in the root zone (Fig. 3), reported absorption in the *C. rotundus* is comparatively small. However, many factors, such as total and plant available concentrations, method of cultivation and fertilization, soil properties, and species-specific growth rates, affect the concentration of a particular elements in a plant (Warman et al., 2005). When compared to rice plants that are the main crop in the study area, the four wetland plant species are potentially valuable and good candidates for uptake of N, Ca, P, Mg, Na, K, Si, Cu, Zn, Mn, Fe, Cr, and Ni (Janyszek-Sołtysiak et al., 2021).

3.2. Nutrient and metal contents of shoots and roots in the four wetland plant species grown in the Thaulla area

The observed values for total N (mg/kg) in shoots of the four species varied from 2005 to 2232 mg/kg, while N in roots was in the range of 1769 to 2168 mg/kg (Table 1). Total N (mg/kg) was not significantly different ($p > 0.05$) for either shoots or roots of the selected plant

Table 1
Nutrient and other metal content of plant' shoots & roots in different aquatic plants in the Thaulla area (mg/kg).

Variety	*Typha angustifolia*		*Eleocharis dulcis*		*Cyperus rotundus*		*Schoenoplectus grossus*	
Parameter	In Shoots	In Roots	In Shoots	In Roots	In Shoots	In Roots	In Shoots	In Roots
N	$2230^a \pm 399$	$1970^a \pm 430$	$2010^a \pm 730$	$2170^a \pm 865$	$2010^a \pm 406$	$2130^a \pm 790$	$2020^a \pm 701$	$1770^a \pm 857$
P	$1650^a \pm 280$	$1350^b \pm 290$	$1930^a \pm 512$	$1450^b \pm 494$	$1870^a \pm 531$	$1280^b \pm 270$	$1940^a \pm 754$	$1600^b \pm 801$
K	$11800^a \pm 2280$	$7290^b \pm 2510$	$2850^a \pm 2050$	$1930^b \pm 1220$	$8370^a \pm 2540$	$6020^b \pm 4320$	$4640^a \pm 2720$	$1800^b \pm 1550$
Na	$61400^a \pm 13,700$	$50000^b \pm 11,800$	$30400^a \pm 5420$	$21700^b \pm 7840$	$41500^a \pm 18,500$	$16900^b \pm 12,700$	$32500^a \pm 12,400$	$19800^b \pm 6070$
Mg	$21900^a \pm 3620$	$16300^b \pm 2780$	$7830^a \pm 1830$	$9590^b \pm 2540$	$9780^a \pm 2240$	$7200^b \pm 1540$	$6990^a \pm 1930$	$7510^b \pm 1430$
Ca	$53200^a \pm 7730$	$41800^a \pm 13,200$	$11800^a \pm 6160$	$19000^a \pm 8040$	$12100^a \pm 4980$	$16000^a \pm 4410$	$9830^a \pm 4060$	$13800^a \pm 3340$
Zn	$10.1^b \pm 5.0$	$11.9^a \pm 4.9$	$2.64^b \pm 2.5$	$6.90^a \pm 6.4$	$3.07^b \pm 1.8$	$8.27^a \pm 2.9$	$3.23^b \pm 3.0$	$5.60^a \pm 3.0$
Cu	$31.7^a \pm 8.1$	$31.2^a \pm 8.4$	$12.6^a \pm 13.7$	$9.61^a \pm 4.0$	$7.64^a \pm 4.4$	$14.9^a \pm 6.1$	$12.9^a \pm 16.3$	$16.9^a \pm 11.8$
Fe	$3650^b \pm 3340$	$2200^a \pm 2370$	$1660^b \pm 1440$	$5920^a \pm 5680$	$1670^b \pm 1770$	$7170^a \pm 1500$	$651^b \pm 602$	$4540^a \pm 2530$
Mn	$468^a \pm 312$	$455^a \pm 250$	$1630^a \pm 946$	$1670^a \pm 443$	$2070^a \pm 1260$	$917^a \pm 390$	$671^a \pm 305$	$554^a \pm 334$
As	$0.61^a \pm 0.3$	$0.51^a \pm 0.4$	$0.27^a \pm 0.3$	$0.19^a \pm 0.3$	$0.26^a \pm 0.2$	$0.16^a \pm 0.2$	$0.18^a \pm 0.3$	$0.16^a \pm 0.2$
Pb	$1.02^a \pm 1.3$	$2.42^a \pm 3.8$	$0.22^a \pm 0.5$	$0.66^a \pm 1.0$	$0.20^a \pm 0.3$	$0.51^a \pm 0.6$	$2.08^a \pm 4.8$	$1.17^a \pm 0.9$
Cd	$0.28^b \pm 0.5$	$0.33^a \pm 0.5$	$0.17^b \pm 0.2$	$0.52^a \pm 0.3$	$0.21^b \pm 0.2$	$0.65^a \pm 0.1$	$0.12^b \pm 0.1$	$0.45^a \pm 0.2$

Mean values (±SD) and mean with the same letters in the same raw are not significantly different at $P < 0.05$.

Table 2
Biological translocation factor, Biological concentration factor, Biological accumulation factor of nutrient and other metal content of four plant species (mg/kg).

Types	*Typha angustifolia*			*Eleocharis dulcis*			*Cyperus rotundus*			*Schoenoplectus grossus*		
Parameter	Shoot:Root (BTF)	Root:Soil (BCF)	Shoot:Soil (BAF)	Shoot:Root (BTF)	Root:Soil (BCF)	Shoot:Soil (BAF)	Shoot:Root (BTF)	Root:Soil (BCF)	Shoot:Soil (BAF)	Shoot:Root (BTF)	Root:Soil (BCF)	Shoot:Soil (BAF)
N	$1.14^{b} \pm 0.9$	$4.98^{a} \pm 2.8$	$5.66^{a} \pm 2.6$	$0.93^{b} \pm 0.8$	$5.14^{a} \pm 7.3$	$4.77^{a} \pm 6.2$	$0.94^{b} \pm 0.5$	$4.91^{a} \pm 2.7$	$4.62^{a} \pm 1.4$	$1.14^{b} \pm 0.8$	$3.34^{a} \pm 5.2$	$3.81^{a} \pm 4.3$
P	$1.22^{b} \pm 1.0$	$8.84^{a} \pm 1.3$	$10.8^{a} \pm 1.2$	$1.34^{b} \pm 1.0$	$23.5^{a} \pm 12.1$	$31.5^{a} \pm 12.6$	$1.46^{b} \pm 2.0$	$20.2^{a} \pm 17.1$	$29.5^{a} \pm 33.7$	$1.21^{b} \pm 0.9$	$18.9^{a} \pm 31.6$	$22.9^{a} \pm 29.7$
K	$1.62^{a} \pm 0.9$	$8.77^{a} \pm 12.3$	$14.2^{a} \pm 11.2$	$1.48^{a} \pm 1.7$	$2.70^{a} \pm 8.3$	$3.99^{a} \pm 13.9$	$1.39^{a} \pm 0.6$	$10.1^{a} \pm 20.4$	$14.1^{a} \pm 12.0$	$2.58^{a} \pm 1.8$	$2.21^{a} \pm 1.7$	$5.72^{a} \pm 2.9$
Na	$1.23^{b} \pm 1.2$	$8.86^{a} \pm 13.8$	$10.9^{a} \pm 16.0$	$1.40^{b} \pm 0.7$	$5.36^{a} \pm 4.4$	$7.53^{a} \pm 3.0$	$2.45^{b} \pm 1.5$	$3.33^{a} \pm 6.6$	$8.16^{a} \pm 9.7$	$1.64^{b} \pm 2.0$	$5.13^{a} \pm 2.8$	$8.41^{a} \pm 5.7$
Mg	$1.35^{a} \pm 1.3$	$1.50^{a} \pm 0.9$	$2.02^{a} \pm 1.1$	$0.82^{a} \pm 0.7$	$1.10^{a} \pm 1.5$	$0.90^{a} \pm 1.1$	$1.36^{a} \pm 1.5$	$1.10^{a} \pm 0.6$	$1.50^{a} \pm 0.9$	$0.93^{a} \pm 1.4$	$1.20^{a} \pm 1.6$	$0.11^{a} \pm 2.2$
Ca	$1.27^{a} \pm 0.6$	$5.27^{a} \pm 3.6$	$6.71^{a} \pm 2.1$	$0.62^{a} \pm 0.8$	$1.92^{a} \pm 4.2$	$1.19^{a} \pm 3.2$	$0.75^{a} \pm 1.1$	$2.99^{a} \pm 2.3$	$2.25^{a} \pm 2.6$	$0.71^{a} \pm 1.2$	$1.90^{a} \pm 2.2$	$1.35^{a} \pm 2.7$
Zn	$0.85^{a} \pm 1.0$	$0.95^{a} \pm 0.9$	$0.81^{a} \pm 0.9$	$0.38^{a} \pm 0.4$	$0.50^{a} \pm 1.5$	$0.19^{a} \pm 0.6$	$0.37^{a} \pm 0.6$	$1.06^{a} \pm 1.2$	$0.39^{a} \pm 0.8$	$0.58^{a} \pm 1.0$	$0.75^{a} \pm 1.1$	$0.43^{a} \pm 1.1$
Cu	$1.02^{a} \pm 1.0$	$0.90^{a} \pm 0.3$	$0.92^{a} \pm 0.3$	$1.31^{a} \pm 3.4$	$0.30^{a} \pm 0.3$	$0.39^{a} \pm 0.9$	$0.51^{a} \pm 0.7$	$0.63^{a} \pm 1.2$	$0.32^{a} \pm 0.9$	$0.77^{a} \pm 1.4$	$0.91^{a} \pm 2.8$	$0.70^{a} \pm 3.9$
Fe	$1.66^{a} \pm 1.41$	$0.10^{a} \pm 0.3$	$0.16^{a} \pm 0.4$	$0.28^{a} \pm 0.3$	$0.24^{a} \pm 1.2$	$0.07^{a} \pm 0.3$	$0.23^{a} \pm 1.2$	$0.39^{a} \pm 0.4$	$0.09^{a} \pm 0.5$	$0.14^{a} \pm 0.2$	$0.32^{a} \pm 1.5$	$0.05^{a} \pm 0.4$
Mn	$1.03^{a} \pm 1.2$	$0.55^{a} \pm 0.7$	$0.57^{a} \pm 0.9$	$0.98^{a} \pm 2.1$	$2.09^{a} \pm 2.5$	$2.05^{a} \pm 5.3$	$2.26^{a} \pm 3.2$	$1.45^{a} \pm 2.9$	$3.27^{a} \pm 9.2$	$1.21^{a} \pm 0.9$	$0.81^{a} \pm 0.7$	$0.98^{a} \pm 0.6$
As	$1.20^{a} \pm 0.8$	ND	ND	$1.42^{a} \pm 1.2$	ND	ND	$1.63^{a} \pm 1.0$	ND	ND	$1.13^{a} \pm 1.4$	ND	ND
Pb	$0.42^{a} \pm 0.3$	ND	ND	$0.33^{a} \pm 0.5$	ND	ND	$0.39^{a} \pm 0.5$	ND	ND	$1.78^{a} \pm 4.9$	ND	ND
Cd	$0.85^{a} \pm 1.0$	$0.18^{a} \pm 0.8$	$0.15^{a} \pm 0.8$	$0.33^{a} \pm 0.5$	$0.25^{a} \pm 1.0$	$0.08^{a} \pm 0.5$	$0.32^{a} \pm 1.2$	$0.41^{a} \pm 0.5$	$0.13^{a} \pm 0.6$	$0.27^{a} \pm 0.4$	$0.37^{a} \pm 1.3$	$0.10^{a} \pm 0.6$

Mean values (±SD) and mean with the same letters in the same raw are not significantly different at $P < 0.05$.

varieties in the Thaulla area (Table 1). According to a previous study, *C. rotundus,* naturally grown on the Thaulla area of *Ulankulama* tank, displayed significantly higher N (700 mg/kg) in shoots than in roots (Abeysingha et al., 2020).

Total P (mg/kg) values in shoots of the four plant types ranged from 1647 to 1939 mg/kg, while P in their roots varied from 1281 to 1603 mg/kg. The statistical analysis showed a significantly higher P content ($p < 0.05$) in shoots than in the roots of the four plant species. We observed a similar trend for K, which had significantly higher K concentrations in shoots than in roots (Table 1). Notably, wetland plants have special physiological features/processes, such as cluster roots, to accumulate essential nutrients such as N and P (Zedler, 2010).

Considering the remaining elemental concentrations tested in the four sedges, significant differences were observed in Na, Mg, Zn, Fe, and Cd, wherein Na and Mg contents of all four species were significantly higher in shoots than roots. However, Zn, Fe, and Cd show significantly higher root concentrations than shoots (Table 1). A study in Uttarpradesh India, where *T. angustifolia* was sampled from a wetland polluted with distillery and tannery effluent showed Cd, Cu, Cr, Fe, and Pb significantly higher in roots than in shoots (Yadav and Chandra, 2011). Hyperaccumulating plants are capable of up-taking metals in their shoots at a level of more than 1000 mg/kg on a dry weight basis (Baker and Brooks, 1989; Simon, 2006). Considering the results of Na, Mg, Ca, and Fe concentrations in shoots, all four plant species exhibited hyperaccumulator status.

3.3. *Variation of soil properties associated with the root zone areas*

3.3.1. *Variation of soil pH and electrical conductivity (EC)*

The pH of the soil root zone (0–15 cm) ranged from 8.01 to 9.25 (mean ± SD: 8.5 ± 0.52) indicating moderate to strong basic conditions. The soil pH is also affected by the waterlogging conditions. Furthermore, soil pH is an important parameter in determining nutrient availability, microbial activity, physical soil conditions, fauna and flora development, chemical reactions, and nutrient cycles (Wagh et al., 2013). Slightly basic soil pH increases the availability of macronutrients, including N, K, Ca, Mg, and S (McCauley et al., 2009).

Electrical conductivity is a proxy for the quantity of ionic salts in the soil. The EC of the Thaulla area in the root zone (0–15 cm) ranged from 0.003 to 0.007 dS/m (mean ± SD: 0.005 ± 0.002 dS/m). This indicates that the soils of Thaulla area are non-saline. The main soil types in the study area are Reddish Brown Earths (RBE) and Low Humic Gley (LHG) soils, and their associations have EC values in ranges of 0.3 to 0.6 dS/cm (Vidyarathna et al., 2008). The average EC for soils in root zone areas of sedges in the Mankadawala tank exceeded this range. This may be attributed to a higher accumulation of different electrolytes when water flows through the Thaulla area.

3.3.2. *Nutrient and metal contents in the rhizosphere soil*

The values for total N (mg/kg) in the root zone under the four plant species in the Thaulla area varied from 394 to 530 mg/kg. Comparing the four-root zone soils in the Thaulla region, the total N (mg/kg) value was not significantly different ($p > 0.05$) (Fig. 3a). We observed a similar trend for P and K, which were not significantly different among species (Fig. 3a). Total P concentration of RBE soils in the Anuradhapura district varied from 1.6 to 20 mg/kg (Karunadasa and Duminda, 2013). Based on these values, our studied area had an accumulation of P. Abeysingha et al. (2016) also found P accumulation in the Thaulla area of the Ulankulama tank in Sri Lanka.

According to these results, total Ca, Zn, Fe, and Cd values in the rooting zone of the four plant species were significantly different ($p < 0.05$). *T. angustifolia* and *E. dulcis* root zone soil in the Thaulla area demonstrated greater values for Fe ($p < 0.05$) than the other species, and the *E. dulcis* root zone contained more Cd than that of *S. grossus.* Comparing the four root zone soils in the Thaulla region, the total Na, Mg, Cu, and Mn (mg/kg) values were not significantly different ($p > 0.05$) (Fig. 3).

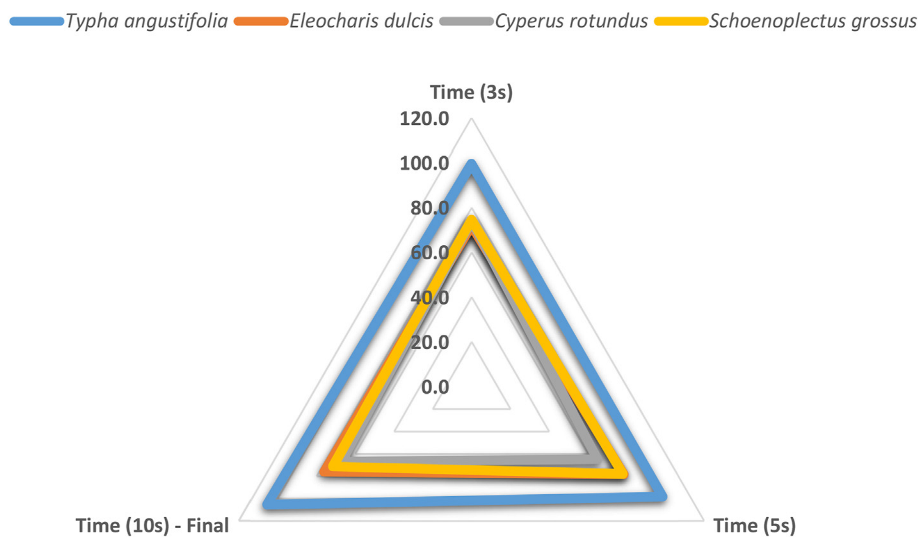

Fig. 4. Aesthetic appeal evaluation of four selected aquatic species.

3.4. Evaluation of phytoextraction behavior

Biological translocation, concentration, and accumulation factors (BTF, BCF, and BAF) for nutrients and metals were assessed to determine the best plant species for phytoextraction (Table 2). These factors are generally used for the assessments of metal phytoextraction behaviour. However, we used the same approach to determine the phytoextraction behaviour of nutrients. These factors were not significantly different among the four plant species for nutrients or metals ($p > 0.05$). BTF measures the internal mobility of a given element across plant components (Deng et al., 2004). Among the elements determined, Fe and Na are the most mobile elements for *T. angustifolia* and *C. rotundus,* respectively. However, K is the most mobile element (higher BTF) for *E. dulcis* and *S. grossus*. The metalloid As shows higher BTF among the metals for all four plant species.

The biological concentration factor (BCF) is defined as the metal concentration ratio in root to soil (Kafle et al., 2022). A BCF value higher than one may indicate that a plant species could act as a hyperaccumulator (Bonanno and Cirelli, 2017). Based on the BCF, all four species were hyperaccumulators for N, P, K, Na, Mg, and Ca (Table 2). Tolerant plants tend to limit metal transfer from soil to root and from root to shoot, and results in less metal accumulation in their biomass. In contrast, hyperaccumulators actively take up and translocate metals into their aboveground biomass (Yoon et al., 2006). Plants with BAF, BCF, and BTF >1 have the potential to be used in phytoextraction (Yoon et al., 2006). This study demonstrated the phytoextraction potential for various nutrients and metals based on the BAF, BCF, and BTF metrics of the four species. For comparison, Song et al. (2015) studied 12 wild plants and showed two plants (*P. capitatum* and *H. debilis)* with higher BCF and BTF.

Jaja et al. (2023) conducted a multiyear experiment in which they demonstrated that cultivation of native vegetation was an effective approach for remediation of excess nitrates-N, P, and heavy metals from surface and sub-surface soil zones. There may be some plant species which have higher phytoextraction behaviour in these meadow (Thaulla) areas of different tanks and those plants can be further employed to remove nutrients and heavy metals. Similar studies indicated that removing heavy metals through harvesting biomass is an efficient technique (Vamerali et al., 2010; Yan et al., 2020).

3.5. Aesthetic appeal evaluation of four sedge species

To determine the species with most suitable visual appeal, the four plant species were evaluated for scenic beauty according to a five-point hedonic scale (Excellent 8–10, Good 6–8, Medium 4–6, General 2–4, Poor 0–2) (Fig. 4). The Friedman non-parametric test evaluated the overall visual attractiveness of the four sedges and showed a significant difference ($p < 0.05$) among the four plant species. Based on the radar chart (Fig. 4), *T. angustifolia* had a significantly ($p < 0.05$) higher evaluator acceptance than the other species.

Weir and Doty (2016) highlighted the importance of social acceptance evaluation for phytoremediation on a gas production site converted to a public park. They showed the visual appeal of the selected plants is an attribute to the social acceptance of phytoremediation techniques. Thus, the present study also considered the visual appeal as an important attribute of selecting the best plant species. Fig. 5 shows pictures of the selected plants at the sampling location for this study. The local community uses all these plants for making mats and baskets and as a source of fodder. Therefore, the nutrients and metals absorbed by these plants will be removed from the tank water system as the community harvests these sedges.

All these plant species have the potential to be introduced to Thaulla areas considering their phytoextraction ability. *T. angustifolia*, with its aesthetic appeal, will be a good option to cultivate in the Thaulla areas in tanks and other constructed wetlands in the dry and intermediate zones of the country. However, studying the species-specific ecology of these plants and other less abundant sedge species in Thaulla areas are suggested. Since we considered only the most abundant plant types in the area, there may be better hyperaccumulating sedge species available in the Thaulla area. However, the results of this study are useful to watershed managers, especially when restoring the Thaulla areas of tanks located in the dry and intermediate zones of the country. Restoration of these wetlands or Thaulla areas using locally available plants is a nature-based solution. As such, these nature-based solutions will improve biodiversity and nature's contribution to people's wellbeing (Cambronero et al., 2023) by providing raw materials for mat and basket manufacturing cottage industry and aesthetics attributes. More studies are suggested to investigate the possibility of the phytoextraction ability of these plants with their growth rates under different concentrations of trace and heavy metals so that these plants can be introduced to constructed wetlands.

Fig. 5. Four aquatic species evaluated in *Thaulla* area of Mankadawala tank in Sri Lanka.

4. Conclusions

This study examined four naturally growing aquatic plant species capability of taking up of nutrients and metals in a meadow (Thaulla area) of Ulankulama tank in the dry zone of Sri Lanka. Among the four species, *S. grossus* demonstrated a higher affinity for P, while *T. angustifolia* demonstrated greater affinity for Na, Mg, Ca, Zn and Cu than the other species. Moreover, *E. dulcis* and *C. rotundus* showed greater affinity for Mn than the other two sedge species. Statistical analysis revealed a significantly higher P content in the shoots than the roots of all four varieties, while P showed a higher tendency of accumulation in the soil. All four species had BAF (roots/soil), BCF (shoots/soil), and BTF (shoots/roots) values > 1, inferring potential use as effective plants for phytoremediation. Overall, *T. angustifolia*, with its greater potential for nutrient and metal accumulation and its high aesthetic appeal, was selected as the preferred species for phytoremediation applications in wetland environments of Sri Lanka.

Data availability statement

Data gathered from the study can be shared at request.

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Ethical responsibilities of authors

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

CRediT authorship contribution statement

M.D.D. Rodrigo: Investigation, Formal analysis, Data curation. **N.S. Abeysingha:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **D.M.S. Duminda:** Resources, Investigation, Formal analysis, Conceptualization. **Ram L. Ray:** Writing – original draft, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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