

A comprehensive Health Risk Assessment Associated with Bioaccumulation of Heavy Metals and Nutrients in selected Macrophytes of Loktak Lake, Manipur, India

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Research Article

Keywords: Bioaccumulation, macrophytes, heavy metals, health risk, target hazard quotient (THQ), hazard index (HI), Loktak Lake

Posted Date: April 18th, 2023

DOI: <https://doi.org/10.21203/rs.3.rs-2619571/v1>

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on September 15th, 2023. See the published version at <https://doi.org/10.1007/s11356-023-29606-2>.

Abstract

A comprehensive assessment was conducted to evaluate the accumulation of selected heavy metals and nutrients in 10 dominant macrophyte species growing in the Loktak Lake, a Ramsar site, and to assess the potential health risks associated with the consumption of the edible plants. The concentrations of nutrients such as total phosphorus (TP), total nitrogen (TN), potassium (K), calcium (Ca), magnesium (Mg), and heavy metals such as copper (Cu), manganese (Mn), zinc (Zn), and iron (Fe) were measured, and found to be present in the order of plant > sediment > water. The bioaccumulation factors (BAFs) revealed high efficiency of most plants to accumulate heavy metals and nutrients in their tissues from the lake water and sediments, indicating their potential to be used as phytoremediators. Translocation factors (TFs) were also estimated to determine the efficiency of the plants to translocate elements from root to shoot. *Colocasia esculenta* and *Polygonum perfoliatum* were found to exhibit the highest BAF and TF values for most of the parameters. Target hazard quotients (THQs) revealed potential health risk associated with one or more heavy metals in the plants, except for Zn whose THQ values were below the level of concern in all the edible plant species. The hazard index (HI) signifying potential non-carcinogenic health risk from the combined effects of all the heavy metals was found to be highest for *Polygonum perfoliatum*, indicating a potentially higher risk to health if this edible macrophyte is regularly consumed in higher quantities and may pose long-term health effects to the exposed population.

Introduction

Wetlands are important freshwater ecosystems that have the capacity to assimilate various nutrients and pollutants, and purify the water (Joyce 2012; Singh et al. 2017). Presence of nutrients and trace metals in safe concentrations plays a significant role in ecohydrological and biological processes, but concentrations above certain threshold levels can result in adverse effects. Thus, excessive loads of nutrients and heavy metals may significantly threaten the ecological health of the wetlands. The deposition of heavy metals in water and sediments can drastically degrade their quality, and due to their toxic, persistent, and bioaccumulative nature, they can undergo a biomagnification process in the aquatic food chain, consequently causing harm to aquatic life as well as to humans (Rinklebe et al. 2016). Similarly, excessive amounts of nutrients can lead to eutrophication of aquatic ecosystems, causing algal blooms, hypoxia, fish mortality, increased sedimentation rates and turbidity of water, along with other undesirable ecohydrological effects (Wisheu et al. 1991; Laishram et al. 2022). The wetland sediments and plants tend to accumulate the contaminants entering the water body through runoff processes from different natural and anthropogenic sources, in varying degrees (Li et al. 2006; Adekola and Eletta 2007; Lu et al. 2011; Singh et al. 2017). Aquatic plants and macrophytes take up and accumulate most of these contaminants through their roots and shoots due to their fast growth and high biomass (Bonanno and Lo Giudice 2010; Matache et al. 2011; Singh et al. 2017). Although this helps in the purification of the water by lowering the concentrations of the pollutants in the water column (Janadeleh and Kameli 2017), but exposure to these edible macrophytes can cause many detrimental health effects on environmental biota. Aquatic plants have also been used as indicators of pollution in many cases to assess wetland pollution (Zayed et al. 1998; Zhu et al. 1999; Kamal et al. 2004; Souza et al. 2013). Thus, the determination of heavy metal concentrations in environmental biota plays a very significant role in assessing the risk on human health resulting from consumption of the contaminated food. The health risk associated with heavy metal accumulation can have non-carcinogenic and carcinogenic effects depending on the heavy metal. Generally, the non-carcinogenic risk is assessed based on the Target Hazard Quotient (THQ), whereas carcinogenic risk assessment is based on the Target Cancer Risk (TCR) (Markmanuel and Horsfall 2016; Yacoub et al. 2021). The assessment of bioaccumulation capacities of plants and macrophytes can also help in identifying specific species that can be potentially utilized for phytoremediation of contaminated aquatic environments in a cost-effective and environment-friendly manner (Salt et al. 1995; Paz-Alberto et al. 2013; Rai et al. 2019). Phytoremediation involves the use of plant and plant roots to remove toxic metals from the soil/water, or to eliminate the bioavailability of toxic metals in the external environment through the process of phytoextraction, rhizofiltration, or phytostabilisation (Salt et al. 1995; Rai et al. 2019).

The Loktak Lake is one of the most important freshwater wetlands in India, known for its biodiversity, ecohydrological significance and socio-economic benefits. In recent years, the ecological health and environmental status of the lake have been at risk of major deterioration due to anthropogenic disturbances such as uncontrolled discharge of pollutants, including sewage, municipal and domestic wastes, and agricultural runoff from the surrounding catchment. In addition to the unchecked discharges, the development of the Loktak Multipurpose Project has also affected the flushing of the lake water to some extent, causing pollutants to deposit and accumulate within the water body (Singh et al. 2013). Although a handful of studies have been carried out on the water quality of the lake, very limited research works on heavy metal/nutrient accumulation in the lake's aquatic plants have been reported (Meitei and Prasad 2016). The present study is carried out with lake water, sediments, and some selective macrophyte species which have not

been reported previously. Thus, the study provides a significant result that contributes to the knowledge of bioaccumulation capacities as well as translocation efficiencies of the macrophyte species found in the study area, helps determine their phytoremediation potential, and investigates the potential health risks associated with the consumption of edible macrophytes of the lake.

Study Area

Loktak Lake is the largest freshwater lake in Northeast India, located between longitudes 93°46' – 93°55' E and latitudes 24°25' – 24°41' N, in the southern part of the Manipur valley, at an altitude of about 770 m above msl (NWA 2009). The wetland is of international importance under the Ramsar Convention due to its rich biodiversity, ecohydrological importance and socio-economic significance. The lake covers a surface area of approximately 246.72 sq. km., with an average recorded depth of about 2.7 m as the lake depth varies from 0.5 to 4.58 m (LDA and WISA 1999; NWA 2009). The region typically experiences tropical to semi-tropical climatic conditions, with temperatures ranging between 0–35°C and an average annual rainfall of around 1183 mm (WAPCOS 1993; NWA 2009). December-January are generally the coldest months and record the lowest amount of rainfall, while May-July are usually the warmer months that also receive the highest amount of rainfall (Meitei 2006). The sub-catchment area of the lake is mainly characterized by clayey and silty types of soil (NBSS and LUP 2001). There are numerous feeder streams and rivers originating from the western hills of the catchment that flow directly into the lake, carrying with them significant amounts of anthropogenic wastes, consequently affecting the lake water quality (CGWB 2013; Laishram and Alam 2019; Laishram et al. 2022). The lake water finally flows out through the Ungamel channel/Ithai barrage, which serves as the main outlet of the lake located towards the southernmost part of the catchment. About 52% of the lake water is attributed from the western part of the catchment, followed by 27% from direct precipitation, and 21% from other linked feeder channels (LDA and WISA 2002). A unique feature of the lake is the presence of floating vegetation masses locally known as *Phumdis* which are formed by the proliferation of aquatic weeds, vegetation, and organic debris at various stages of decomposition. They vary in shape, size, and thickness, ranging from a few inches to several feet, covering a large portion of the lake, and provide habitat to various endemic flora and fauna. A thick contiguous mat of *Phumdis* covering an area of approximately 40 sq. km. is situated towards the southern part of the lake, which constitutes The Keibul Lamjao National Park, which is the only floating National Park in the world. The park is home to the endemic and endangered brow-antlered deer known as Sangai (*Rucervus eldii eldii*) (Trisal and Manihar 2002) and serves as a significant ecohydrological unit of the lake.

Materials And Methods

Sample collection

Water, sediment, and macrophyte samples were collected from different sites of the lake (Fig. 1). Water samples were collected at a depth of > 1 cm below the water surface in precleaned and properly rinsed (with dilute HNO₃ and deionized water) high-density polyethylene (HDPE) bottles. Sediment samples were collected from a depth of 0 to 20 cm from the sediment surface in polyethylene zip-lock bags. Macrophyte species were identified and samples were collected in triplicates including their roots, wrapped in paper, and brought to the laboratory for analysis. The water samples for heavy metal analysis were treated with 1:1 (v/v) HNO₃ solution, and those for analysis of total nitrogen and total phosphorus were treated with 1:1 (v/v) H₂SO₄ solution to preserve the samples (pH < 2) and stored in the laboratory at 4°C, as per standard protocols given by the American Public Health Association (APHA 2005). *In-situ* analysis for parameters such as pH and EC were also carried out for the water samples in the field condition using field test kits/sensors (Eutech).

Sample Preparation And Analysis

The sediment samples were dried in the oven at 70°C for 24–48 hours until fully dry, ground using mortar and pestle to form powder, and then sieved to remove any coarse particles. For analysis of heavy metals, the sediment samples were first digested following the dry ashing method in which 1 g of each of the samples were placed in a crucible, heated to 500–600°C in a muffle furnace for 3 hours, and kept inside overnight. Subsequently, the ashes were digested with 10 ml of 2 N HCl, stirred, and kept aside for 1 hour. After 1 hour, the extracted samples were filtered using Whatman filter paper to remove the residues, followed by dilution of the filtrates to 50 ml using deionized water. The fresh macrophyte samples were washed thoroughly with tap water and then rinsed with deionized water, followed by their separation into roots and shoots, after which they were dried in the oven at 70°C for 24–48 hours. Care was taken to spread out the materials loosely in the oven to allow free movement of moisture-laden air. Once completely dry, the samples were

ground into powder form and placed in appropriately labeled polyethylene containers for subsequent analysis. Similar to sediments, the macrophyte samples were also digested by the dry ashing method using 0.5 g of each sample to obtain 50 ml diluted filtrate for further analysis. Water samples were also filtered using 0.45 µm Whatman filter paper for heavy metal analysis. The extracted samples were finally measured for selected heavy metals Cu, Zn, Mn, and Fe, using atomic absorption spectrophotometer (AAS) (Perkin-Elmer AAnalyst 200). Similarly, the digested sediment and macrophyte samples were also measured for selected nutrients such as total phosphorus (TP), total nitrogen (TN), calcium (Ca), magnesium (Mg), and potassium (K). TP was measured following the ammonium molybdate vanadate method using the spectrophotometer, TN was measured by the Kjeldahl method, Ca and Mg were measured using AAS, and K was measured using the flame photometer. Whereas, for the water samples, TP was measured by persulphate digestion of the water followed by the stannous chloride method using spectrophotometer (Thermo-scientific Genesys 180), TN was measured with TOC/TN analyzer (Shimadzu TNM-L ROHS), Ca and Mg were measured by titration method, and K was measured using flame photometer (Systronics 128) (APHA 2005).

Bioaccumulation And Translocation Factors

The bioaccumulation factor (BAF) has been calculated to indicate the efficiency of a plant species to accumulate heavy metals or nutrients into its tissues from the surrounding environment such as water and sediments (Ladislav et al. 2012; Singh et al. 2017). BAF can be defined as the ratio of selected metal/nutrient concentration present in the plant tissues to that present in water or sediment (Nabi 2021). The larger the BAF value, the greater is the ability of the plant to absorb metals/nutrients from the medium in which they grow (Ha et al. 2011; Favas et al. 2012).

$$BAF = \frac{C_p}{C_e}$$

where C_p = mean metal/nutrient concentration in plant part, expressed in mg/kg, and C_s = mean metal/nutrient concentration in the external environment, i.e., water or sediments, expressed in mg/kg. According to the BAF values, the plants can be categorized as excluder (BAF < 1), accumulator (BAF = 1 to 10), and hyperaccumulator (BAF > 1) (Baker 1981; Jha et al. 2016).

The translocation factor (TF) has been calculated to determine the metal/nutrient translocation properties of the plants from their roots to shoots (Janadeleh and Kameli 2017). The TF is expressed as the ratio of mean metal/nutrient concentration in shoots to that in roots (Zacchini et al. 2009).

$$TF = \frac{C_{shoot}}{C_{root}}$$

where C_{shoot} = mean metal/nutrient concentration present in the shoots, expressed in mg/kg, and C_{root} = mean metal/nutrient concentration present in the roots, expressed in mg/kg. TF value greater than 1 signifies that the plant effectively translocates metals/nutrients from its roots to shoots (Baker and Brooks 1989; Jha et al. 2016). Plants that have BAF and TF values > 1 can be used as bio-accumulators; those having BAF values > 1 and TF values < 1 can be used as phyto-stabilizers; while those that have BAF values < 1 and TF values > 1 can be used as phytoextractors (Usman et al. 2013; Sopyan et al. 2014; Takarina and Pin 2017; Purwaningdyah and Takarina 2020).

Human Health Risk Assessment

The health risk assessment of trace metals due to the prolonged consumption of edible macrophytes from the study area was carried out by calculating the estimated daily intake (EDI) of trace metals, the target hazard quotient (THQ), and the hazard index (HI) (USEPA 2011; Fang et al. 2014). These calculations are based on the assumption that the ingested dose is equal to the absorbed dose (USEPA 1989). The EDI depends on the metal concentrations in the edible macrophyte species, the daily consumption amount, and the average body weight of consumers (Song et al. 2009; Li et al. 2013; Islam et al. 2020).

$$EDI = \frac{C_m \times IR}{BW}$$

where C_m = concentration of metal in the edible plant, IR = ingestion rate, which is assumed to be 0.1 kg/day per adult, and BW = body weight of consumer, assumed to be 70 kg for an adult (Alhashemi et al. 2012; Janadeleh and Kameli 2017). The THQ is an estimate of the non-carcinogenic risk level due to metal exposure (Javed and Usmani 2016; Elhaddad et al. 2022). THQ is a dimensionless value and is calculated as follows (USEPA 2011)

$$THQ = \frac{EF \times ED \times IR \times C_m \times 10^{-3}}{RFD \times BW \times AT}$$

where EF is exposure frequency (365 days/year), ED is exposure duration (70 years) which is considered to be the average life span of a human (USEPA 1991), RFD is the oral reference dose (mg/kg/day), AT is the average exposure time (365 days/year $\times$ life span), and IR , C_m , BW have been defined above. The oral reference doses for Cu, Mn, Zn, and Fe were 0.04, 0.14, 0.3, and 0.7 mg/kg/day, respectively (USEPA 2012). THQ value less than 1 indicates that the exposed population has a lower chance of experiencing adverse effects due to metal contamination; while THQ value equal to or greater than 1 indicates potential health risk to the exposed population (Wang et al. 2005; Janadeleh and Kameli 2017; Islam et al. 2017; Yacoub et al. 2021). Finally, HI was calculated to determine the overall potential non-carcinogenic health risk posed by all the heavy metals measured combined, which is expressed as the sum total of all individual THQs (USEPA 2011; Javed and Usmani 2016; Janadeleh and Kardani 2016; Janadeleh and Kameli 2017).

$$HI = \sum_{i=1}^n THQ_i$$

where i represents each metal, and n is the total number of heavy metals analysed. HI value exceeding 1 indicates significant potential health effects associated with the heavy metals under consideration (Huang et al. 2008; Elowa et al. 2022).

Statistical analysis

The results of the experimental data have been presented as mean $\pm$ standard deviation (SD) values. The required calculations and graphical presentations involved in analysis of the experimental data, along with correlation analysis were carried out using MS-EXCEL-2019. The hierarchical cluster analysis (CA) was carried out using SPSS software to group the macrophyte species based on similar bioaccumulation capacities from the external environment, and their results were presented in the form of a dendrogram (Tiri et al. 2017; Prusty et al. 2018).

Results And Discussion

Heavy metal and nutrient concentrations in water and sediments

The concentrations of the selected nutrients and heavy metals in the lake water and sediments from the sites where the macrophyte samples were collected, along with the respective permissible limits prescribed by national and international regulatory bodies (BIS 2012; WHO 1996) have been presented in Table 1. The pH of the water was found to be neutral to slightly alkaline in nature (7.06–8.32) and well within the permissible range of 6.5 to 8.5. Similarly, the EC of all water samples were found under the permissible limit of 250 μ S/cm (152.6–192.7 μ S/cm). The TP concentration in the water was found to range from 0.47–1.61 ppm, and that of TN ranged between 0.43–3.37 ppm. The highest concentrations of these two key nutrients were observed in the northern region of the lake, close to the discharge points of the lake's feeder rivers, particularly the Nambul River which passes through the heart of the state's capital city, Imphal, carrying with them sewage, domestic and municipal wastes, in addition to the agricultural runoff from the surrounding regions of the lake. The concentrations of alkali and alkali earth elements (K, Ca, Mg) in the lake water were found in relatively low levels as per their respective permissible limits. Among the heavy metals measured, the concentration of Fe in the water was found to be higher (0.101–1.134 ppm) than Cu, Mn, and Zn; and Fe level in the lake water towards the northern side exceeded the permissible limit of 0.3 ppm. Concentrations of Cu were found below the permissible limit of 1.5 ppm (ranging between 0.019–0.027 ppm). Similarly, Mn concentrations in water ranged between 0.032–0.085 ppm, which were under the permissible limit of 0.3 ppm; and Zn concentrations ranged between 0.013–0.033 ppm which were also well below the prescribed permissible limit of 15 ppm. Although it was observed that the concentrations of most of the trace elements in the lake water were relatively low with respect to the drinking water quality standards, however, the presence of higher level of Fe concentration in selected sites of the lake may be a cause of concern resulting in ecological damage to the lake and may pose serious adverse effects to human health, if the untreated lake water is regularly consumed on a long-term basis (Ibrahim et al. 2021).

Table 1
Distribution of heavy metals in water and sediments samples of Loktak Lake

Site	Water (Mean ± SD)											
	Parameter	pH	EC	TP	TN	K	Ca	Mg	Cu	Mn	Zn	Fe
	Unit	-	µS/cm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Permissible limit (BIS 2012)	6.5–8.5	250				75	30	1.5	0.3	15	0.3
M1-North		7.06 ± 0.01	192.7 ± 0.05	1.61 ± 0.02	3.37 ± 0.12	5.53 ± 0.02	10.01 ± 0.01	9.72 ± 0.04	0.027 ± 0.003	0.04 ± 0.01	0.033 ± 0.01	1.134 ± 0.01
M2-Core		8.32 ± 0.03	152.6 ± 0.07	0.51 ± 0.04	0.43 ± 0.05	1.8 ± 0.03	12.01 ± 0.02	9.72 ± 0.03	0.022 ± 0.002	0.036 ± 0.002	0.023 ± 0.002	0.101 ± 0.03
M3-Karang		8.21 ± 0.01	158.8 ± 0.04	0.47 ± 0.06	0.43 ± 0.11	1.71 ± 0.02	12.01 ± 0.02	9.72 ± 0.04	0.019 ± 0.001	0.032 ± 0.002	0.027 ± 0.01	0.113 ± 0.02
M4-South		8.03 ± 0.02	156.5 ± 0.03	0.54 ± 0.02	0.39 ± 0.09	1.42 ± 0.04	14.02 ± 0.01	9.72 ± 0.02	0.02 ± 0.001	0.085 ± 0.01	0.013 ± 0.004	0.151 ± 0.01
	Sediments (Mean ± SD)											
	Unit	-	µS/cm	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
	Permissible limit (WHO 1996)								36		50	
M1-North		4.5 ± 0.03	398 ± 0.07	18.24 ± 0.07	4200 ± 0.15	17970 ± 0.04	107.73 ± 0.01	279.12 ± 0.15	6.2 ± 0.001	139.4 ± 0.01	62.25 ± 0.01	983.27 ± 0.03
M2-Core		5.46 ± 0.01	469 ± 0.1	33.65 ± 0.07	4760 ± 0.33	17410 ± 0.07	111.35 ± 0.02	286.07 ± 0.07	5.59 ± 0.002	102.45 ± 0.02	52.09 ± 0.01	962.14 ± 0.05
M3-Karang		5.36 ± 0.04	221 ± 0.08	6.53 ± 0.04	3920 ± 0.24	17770 ± 0.05	134.61 ± 0.02	281.71 ± 0.06	9.58 ± 0.001	111.65 ± 0.02	67.32 ± 0.01	980.06 ± 0.03
M4-South		4.55 ± 0.02	529 ± 0.2	15.16 ± 0.05	6580 ± 0.21	17685 ± 0.05	127.13 ± 0.01	282.31 ± 0.27	6.7 ± 0.001	122.76 ± 0.02	59.41 ± 0.03	968.36 ± 0.02

The concentrations of heavy metals and nutrients in the lake sediments were found to be higher than in the lake water. The pH of the sediments indicated a slightly acidic nature, ranging from 4.5–5.46. Similarly, the EC levels were found to vary between 221–529 μ S/cm, with the highest EC being observed in the southern portion of the lake. The high concentrations of key nutrients such as TP (6.53–33.65 mg/kg) and TN (3920–6580 mg/kg) in the sediments may be attributed to the accumulation and adsorption of the nutrients from the nutrient-laden discharges draining into the lake from the feeder rivers and surrounding catchment, mainly resulting from various anthropogenic discharges and chemical fertilizers from the surrounding agriculture fields. Similarly, concentrations of K, Ca, and Mg were found to range from 17410–17970 mg/kg, 107.73–134.61 mg/kg, and 279.12–286.07 mg/kg, respectively. Similar to the lake water scenario, the concentration of Fe in the lake sediments were found to be much higher than the other heavy metals measured, with Fe levels in the sediments ranging from 962.14–983.27 mg/kg. This high iron content in the sediments may be a result of the weathering, erosion, and settlement of iron-bearing soils from the surrounding catchment eventually getting washed down and accumulating in the lake bottom, along with contributions from the dissolution of water-soluble salts from the feeder streams/rivers (Flefel et al. 2020). In contrast, Cu levels in the sediments were comparatively the lowest, varying between 6.2–9.58 mg/kg, which were well below the permissible limit in soil., i.e., 36 mg/kg. Sources of Cu contamination have been traced to the excessive use of

pesticides (Flefel et al. 2020). Concentrations of Mn ranged between 102.45–139.4 mg/kg and Zn ranged between 52.09–67.32 mg/kg, which exceeded the permissible limit of 50 mg/kg in soil (Table 1).

Heavy Metal And Nutrient Concentrations In Macrophytes

The scientific descriptions of ten (10) different plant/macrophyte species collected from Loktak Lake have been presented in Table 2, of which 9 species are edible and only one species *E. crassipes* is considered as a weed. The estimated concentrations of different heavy metals and nutrients in the roots and shoots of the different macrophytes have been presented in Tables 3 and 4. In terms of the total concentration of nutrients and heavy metals in the overall plant tissues, including both shoot and root, the order of concentration of TP was found as *C. esculenta* > *I. aquatica* = *H. flavum* > *O. javanica* > *Z. latifolia* > *J. repens* > *E. crassipes* > *Oenanthe sp.* > *P. karka* > *P. perfoliatum*. Concentration of TN was found in the order of *I. aquatica* > *J. repens* > *P. perfoliatum* > *E. crassipes* > *O. javanica* > *C. esculenta* > *Z. latifolia* > *H. flavum* > *P. karka* > *Oenanthe sp.* Concentration of K was in the order of *C. esculenta* > *O. javanica* > *H. flavum* > *Oenanthe sp.* > *Z. latifolia* > *P. karka* > *E. crassipes* > *J. repens* > *P. perfoliatum* > *I. aquatica*. Concentration of Ca was in the order of *C. esculenta* > *J. repens* > *Oenanthe sp.* > *E. crassipes* > *O. javanica* > *P. perfoliatum* > *I. aquatica* > *H. flavum* > *Z. latifolia* > *P. karka*. Mg concentration was found in the order of *J. repens* > *E. crassipes* > *P. perfoliatum* > *O. javanica* > *Oenanthe sp.* > *C. esculenta* > *H. flavum* > *I. aquatica* > *Z. latifolia* > *P. karka*. Among the heavy metals analysed, the concentration of Cu was found in the order of *P. perfoliatum* > *Oenanthe sp.* > *I. aquatica* > *C. esculenta* > *O. javanica* > *H. flavum* > *E. crassipes* > *P. karka* > *Z. latifolia* > *J. repens*. Concentration of Mn was in the order of *P. perfoliatum* > *J. repens* > *I. aquatica* > *E. crassipes* > *H. flavum* > *O. javanica* > *Oenanthe sp.* > *C. esculenta* > *Z. latifolia* > *P. karka*. Zn concentration was in the order of *C. esculenta* > *H. flavum* > *O. javanica* > *E. crassipes* > *P. perfoliatum* > *I. aquatica* > *Oenanthe sp.* > *J. repens* > *Z. latifolia* > *P. karka*. And finally, the concentration of Fe was found to be in the order of *I. aquatica* > *P. perfoliatum* > *E. crassipes* > *J. repens* > *C. esculenta* > *Oenanthe sp.* > *O. javanica* > *Z. latifolia* > *H. flavum* > *P. karka*. Graphical depictions of the nutrient and heavy metal concentrations in the roots and shoots of the different macrophyte species have also been presented in Fig. 2.

Table 2

Description of macrophyte species collected from Loktak Lake, Manipur for assessment of bioaccumulation potential

Scientific name	Family	Local name	Plant habit	Use
<i>Phragmites karka</i> (Retz.) Trin. ex Steud.	Poaceae	Tou	Emergent	Fuel, edible
<i>Zizania latifolia</i> Turcz. ex Stapf.	Poaceae	Ishing kambong	Emergent	Edible / medicinal
<i>Hedychium flavum</i> Roxb.	Zingiberaceae	Loklei	Emergent	Edible / medicinal
<i>Polygonum perfoliatum</i> L.	Polygonaceae	Lilhar	Emergent	Edible
<i>Ipomoea aquatica</i> Forssk.	Convolvulaceae	Kolamani	Emergent	Edible
<i>Oenanthe sp.</i>	Apiaceae	Komprek achouba	Emergent	Edible / medicinal
<i>Oenanthe javanica</i> (Blume) DC	Apiaceae	Komprek macha	Emergent	Edible / medicinal
<i>Jussiaea repens</i> Linn.	Onagraceae	Ishing kundo	Emergent	Edible / medicinal
<i>Eichhornia crassipes</i> (Mart.) Solms	Pontederiaceae	Kabokang	Free floating	Weed
<i>Colocasia esculenta</i> (Linn.) Schott	Araceae	Pankhok	Emergent	Edible

Table 3
The concentration of Heavy metal in shoots and roots samples of macrophyte species

Plant	Plant part	Heavy metal concentration (mg/kg) (Mean $\pm$ SD)			
		Cu	Mn	Zn	Fe
<i>P. karka</i>	Shoot	8.66 $\pm$ 0.002	67.99 $\pm$ 0.17	84.45 $\pm$ 0.005	73.55 $\pm$ 0.03
	Root	38.86 $\pm$ 0.002	35.58 $\pm$ 0.02	70.23 $\pm$ 0.009	230.17 $\pm$ 0.02
<i>Z. latifolia</i>	Shoot	10.57 $\pm$ 0.002	109.37 $\pm$ 0.01	56.25 $\pm$ 0.004	101.27 $\pm$ 0.01
	Root	30.53 $\pm$ 0.002	149.41 $\pm$ 0.01	99.8 $\pm$ 0.004	1421.05 $\pm$ 0.02
<i>H. flavum</i>	Shoot	79.56 $\pm$ 0.002	549.13 $\pm$ 0.02	122.09 $\pm$ 0.01	289.83 $\pm$ 0.02
	Root	16.3 $\pm$ 0.001	369.83 $\pm$ 0.07	154.39 $\pm$ 0.02	287.19 $\pm$ 0.02
<i>P. perfoliatum</i>	Shoot	56.87 $\pm$ 0.002	906.84 $\pm$ 0.02	123.4 $\pm$ 0.018	628.19 $\pm$ 0.03
	Root	171.08 $\pm$ 0.005	866.23 $\pm$ 0.1	102.79 $\pm$ 0.005	1695.93 $\pm$ 0.03
<i>I. aquatica</i>	Shoot	44.26 $\pm$ 0.002	486.16 $\pm$ 0.05	66.36 $\pm$ 0.005	798.32 $\pm$ 0.06
	Root	56.26 $\pm$ 0.001	773.63 $\pm$ 0.06	130.32 $\pm$ 0.01	1704.6 $\pm$ 0.01
<i>Oenanthe sp.</i>	Shoot	33.55 $\pm$ 0.002	364.87 $\pm$ 0.02	88.19 $\pm$ 0.002	233.19 $\pm$ 0.05
	Root	81.75 $\pm$ 0.001	409.74 $\pm$ 0.06	100.14 $\pm$ 0.006	1411.15 $\pm$ 0.05
<i>O. javanica</i>	Shoot	56.15 $\pm$ 0.001	469.44 $\pm$ 0.22	129.16 $\pm$ 0.005	349.02 $\pm$ 0.02
	Root	42.21 $\pm$ 0.003	308.92 $\pm$ 0.05	142.53 $\pm$ 0.005	1181.74 $\pm$ 0.02
<i>J. repens</i>	Shoot	7.07 $\pm$ 0.001	339.23 $\pm$ 0.03	86.1 $\pm$ 0.01	299.48 $\pm$ 0.03
	Root	23.47 $\pm$ 0.002	940.83 $\pm$ 0.23	101.21 $\pm$ 0.003	1762.45 $\pm$ 0.02
<i>E. crassipes</i>	Shoot	15.18 $\pm$ 0.0001	402.65 $\pm$ 0.09	71.57 $\pm$ 0.008	338.9 $\pm$ 0.03
	Root	58.14 $\pm$ 0.003	765.71 $\pm$ 0.01	172.72 $\pm$ 0.002	1733.89 $\pm$ 0.05
<i>C. esculenta</i>	Shoot	66.73 $\pm$ 0.001	484.86 $\pm$ 0.03	139.34 $\pm$ 0.017	237.19 $\pm$ 0.04
	Root	32.09 $\pm$ 0.001	239.86 $\pm$ 0.04	163.99 $\pm$ 0.014	1515.33 $\pm$ 0.03

Table 4
The Nutrient concentration in shoots and roots samples of macrophyte species

Plant	Plant part	Nutrient concentration (mg/kg) (Mean $\pm$ SD)				
		TP	TN	K	Ca	Mg
<i>P. karka</i>	Shoot	84.57 $\pm$ 0.004	12320 $\pm$ 0.03	45480 $\pm$ 0.02	46.05 $\pm$ 0.01	269.09 $\pm$ 0.03
	Root	88.26 $\pm$ 0.002	7000 $\pm$ 0.11	29950 $\pm$ 0.06	24.83 $\pm$ 0.02	193.81 $\pm$ 0.03
<i>Z. latifolia</i>	Shoot	205.37 $\pm$ 0.003	14000 $\pm$ 0.06	73690 $\pm$ 0.02	35.35 $\pm$ 0.002	246.9 $\pm$ 0.02
	Root	183.18 $\pm$ 0.01	10360 $\pm$ 0.06	25890 $\pm$ 0.04	101.74 $\pm$ 0.003	348.16 $\pm$ 0.02
<i>H. flavum</i>	Shoot	253.45 $\pm$ 0.002	15120 $\pm$ 0.03	84560 $\pm$ 0.03	1228.09 $\pm$ 0.04	550.72 $\pm$ 0.06
	Root	215.24 $\pm$ 0.02	8120 $\pm$ 0.02	58570 $\pm$ 0.06	323.65 $\pm$ 0.03	553.51 $\pm$ 0.21
<i>P. perfoliatum</i>	Shoot	74.7 $\pm$ 0.02	15680 $\pm$ 0.03	37710 $\pm$ 0.03	4196.56 $\pm$ 0.1	555.72 $\pm$ 0.26
	Root	95.66 $\pm$ 0.07	12880 $\pm$ 0.06	27980 $\pm$ 0.003	2441.3 $\pm$ 0.26	571.84 $\pm$ 0.23
<i>I. aquatica</i>	Shoot	236.19 $\pm$ 0.005	20160 $\pm$ 0.07	35930 $\pm$ 0.01	1132.83 $\pm$ 0.09	551.89 $\pm$ 0.18
	Root	232.5 $\pm$ 0.02	24640 $\pm$ 0.05	26430 $\pm$ 0.003	577.81 $\pm$ 0.02	539.93 $\pm$ 0.07
<i>Oenanthe sp.</i>	Shoot	84.57 $\pm$ 0.01	8680 $\pm$ 0.01	73150 $\pm$ 0.01	8304.41 $\pm$ 0.45	542.25 $\pm$ 0.16
	Root	132.64 $\pm$ 0.01	9800 $\pm$ 0.06	64250 $\pm$ 0.01	4466.93 $\pm$ 0.25	569.03 $\pm$ 0.05
<i>O. javanica</i>	Shoot	218.93 $\pm$ 0.01	15680 $\pm$ 0.01	93300 $\pm$ 0.04	7218.34 $\pm$ 0.22	560.99 $\pm$ 0.11
	Root	193.05 $\pm$ 0.07	10080 $\pm$ 0.01	58130 $\pm$ 0.005	1600.2 $\pm$ 0.02	557.19 $\pm$ 0.18
<i>J. repens</i>	Shoot	144.97 $\pm$ 0.01	11760 $\pm$ 0.01	41480 $\pm$ 0.003	7949.69 $\pm$ 0.78	568.72 $\pm$ 0.05
	Root	163.46 $\pm$ 0.03	17080 $\pm$ 0.02	26660 $\pm$ 0.01	4927.9 $\pm$ 0.12	571.26 $\pm$ 0.19
<i>E. crassipes</i>	Shoot	152.37 $\pm$ 0.01	14840 $\pm$ 0.01	46890 $\pm$ 0.01	8329.16 $\pm$ 0.43	570.56 $\pm$ 0.21
	Root	137.57 $\pm$ 0.01	11200 $\pm$ 0.01	26420 $\pm$ 0.01	3765.24 $\pm$ 0.12	560.67 $\pm$ 0.08
<i>C. esculenta</i>	Shoot	279.34 $\pm$ 0.01	20160 $\pm$ 0.05	168380 $\pm$ 0.01	8094.01 $\pm$ 0.35	551.84 $\pm$ 0.22
	Root	210.31 $\pm$ 0.06	5320 $\pm$ 0.21	58160 $\pm$ 0.01	7952.27 $\pm$ 0.12	554.95 $\pm$ 0.17

Among the nutrients, TP, TN, and K were found to be present in high concentrations in the plant tissues, which can be indicative of high nutrient uptake from the external environment and their retention in the plant tissues (Meitei and Prasad 2016). In general, among the heavy metals analysed, it was observed that Fe and Mn concentrations were highest in the plant tissues, while Cu concentrations were the lowest in most of the plants. Fe concentrations were observed to be much higher than the natural content of 370 mg/kg (Brooks and Robinson 1998) in the roots of most species, namely, *Z. latifolia*, *P. perfoliatum*, *I. aquatica*, *Oenanthe sp.*, *O. javanica*, *J. repens*, *E. crassipes*, and *C. esculenta*, and shoots of a few species, namely, *P. perfoliatum* and *I. aquatica*. High Fe concentration in plant tissues have been reported to cause haemorrhagic necrosis and tissue injury, in addition to activation of oncogenes (Gurzau et al. 2003). Mn concentrations in both shoots and roots of all the plants species studied, except the root of *P. karka*, exceeded the natural content of 52 mg/kg (Brooks and Robinson 1998), and all the plants except *P. karka* and *Z. latifolia* also exceeded the maximum permissible limit of 200 mg/kg (WHO/FAO 1996). Despite its concentrations being the lowest in comparison to the other heavy metals, Cu content in most of the plant species were above the WHO permissible limit of 10 mg/kg, except in the shoots of *P. karka* and *J. repens*, and most even exceeded the phytotoxic range, i.e., 25–40 mg/kg (Chaney 1989). On the other hand, all plants had Zn content below the phytotoxic range of 500–1500 mg/kg (Chaney 1989). However, they did exceed the permissible limit of 0.6 mg/kg as specified by WHO (1996). Although Zn is needed for the development and function of the body, excessive levels can lead to nausea, respiratory disorders, diarrhoea, epigastric pain, focal neuronal deficits, and risk of prostate cancer (Plum et al. 2010; Ohiagu et al. 2020). In most cases, the metal concentrations were greater in the roots compared to the shoots, however higher concentrations of certain metals in the shoots have also been observed in some species as shown in the Table 3 and Fig. 2. The concentrations of nutrients and trace metals in the aquatic macrophytes have also been found to be higher than in the lake water and sediments. The increase in heavy metal

concentrations from the lake water to sediments to the macrophytes suggests further accumulation in fish and then humans, which can ultimately result in various health effects and diseases (Zaigham et al. 2012; Flefel et al. 2020).

Bioaccumulation And Translocation Characteristics Of Macrophytes

Bioaccumulation factor (BAF)

The BAF was calculated to estimate the capacities of the plant species to accumulate heavy metals or nutrients into their tissues from the external environment. BAF values of different macrophyte species for the selected nutrients and heavy metals have been presented in Tables 5 and 6. BAF values have been calculated taking into account both water and sediments as the external media due to the fact that the collected macrophytes grow on *Phumdis*, which absorb nutrients from both the water as well the sediment particles embedded in the vegetative mats, in addition to the bottom sediments that the mats can often come in contact with. Plants exhibiting BAFs greater than 1 are considered to be hyperaccumulators, i.e., having great efficiency to accumulate the selected element in their tissues; and larger BAF values indicate greater accumulative properties (Baker 1981; Ha et al. 2011; Favas et al. 2012; Jha et al. 2016). Considering water as the external environment (Table 5), the BAF values revealed that all the macrophyte species were hyperaccumulators of the selected nutrients and heavy metals from the surrounding lake water. Different plant parts also accumulated the heavy metals and nutrients in varying degrees. BAFs for nutrients such as TP ranged between 85.50-598.16; TN ranged between 3328.38-57935.57; K ranged from 4777.58-98467.84; Ca ranged from 1.77-832.02; and Mg ranged from 19.94–58.83. Similarly, BAFs for the heavy metals including Cu ranged between 350-8957.07; Mn ranged between 418.61-27988.87; Zn ranged between 2142.81-7969.29; and Fe ranged between 298.99-15098.32. The plant tissues thus exhibited significant bioaccumulative capacities of nutrients from the lake water, including TP in the order of *C. esculenta* shoot > *H. flavum* shoot > *I. aquatica* shoot > *I. aquatica* root > *O. javanica* shoot > *H. flavum* root > *C. esculenta* root > *O. javanica* root > *Z. latifolia* shoot > *Z. latifolia* root > *J. repens* root > *J. repens* shoot > *Oenanthe sp.* root > *P. perfoliatum* root > *P. karka* root > *P. perfoliatum* shoot > *P. karka* shoot = *Oenanthe sp.* shoot > *E. crassipes* shoot > *E. crassipes* root. Order of TN accumulation efficiency was *I. aquatica* root > *C. esculenta* shoot > *I. aquatica* shoot > *J. repens* root > *O. javanica* shoot > *P. perfoliatum* shoot > *H. flavum* shoot > *Z. latifolia* shoot > *P. karka* shoot > *J. repens* shoot > *P. perfoliatum* root > *Oenanthe sp.* root > *Z. latifolia* root > *O. javanica* root > *Oenanthe sp.* shoot > *H. flavum* root > *P. karka* root > *C. esculenta* root > *E. crassipes* shoot > *E. crassipes* root. Efficiency of K accumulation was in the order of *C. esculenta* shoot > *O. javanica* shoot > *Oenanthe sp.* shoot > *H. flavum* shoot > *Oenanthe sp.* root > *Z. latifolia* shoot > *H. flavum* root > *C. esculenta* root > *O. javanica* root > *P. karka* shoot > *J. repens* shoot > *P. perfoliatum* shoot > *P. karka* root > *I. aquatica* shoot > *J. repens* root > *P. perfoliatum* root > *I. aquatica* root > *Z. latifolia* root > *E. crassipes* shoot > *E. crassipes* root; that of Ca accumulation was in the order of *E. crassipes* shoot > *C. esculenta* shoot > *C. esculenta* root > *O. javanica* shoot > *Oenanthe sp.* shoot > *J. repens* shoot > *E. crassipes* root > *J. repens* root > *P. perfoliatum* shoot > *Oenanthe sp.* root > *P. perfoliatum* root > *O. javanica* root > *H. flavum* shoot > *I. aquatica* shoot > *I. aquatica* root > *H. flavum* root > *Z. latifolia* root > *P. karka* shoot > *Z. latifolia* shoot > *P. karka* root; and that of Mg accumulation was in the order of *P. perfoliatum* root > *J. repens* root > *E. crassipes* shoot > *Oenanthe sp.* root > *J. repens* shoot > *O. javanica* shoot > *E. crassipes* root > *O. javanica* root > *P. perfoliatum* shoot > *C. esculenta* root > *H. flavum* root > *I. aquatica* shoot > *C. esculenta* shoot > *H. flavum* shoot > *Oenanthe sp.* shoot > *I. aquatica* root > *Z. latifolia* root > *P. karka* shoot > *Z. latifolia* shoot > *P. karka* root. Similarly, significant efficiency of heavy metal accumulation by the plant tissues was observed, with that of Cu in the order of *P. perfoliatum* root > *H. flavum* shoot > *Oenanthe sp.* root > *C. esculenta* shoot > *P. perfoliatum* shoot > *I. aquatica* root > *O. javanica* shoot > *I. aquatica* shoot > *O. javanica* root > *E. crassipes* root > *P. karka* root > *C. esculenta* root > *Oenanthe sp.* shoot > *Z. latifolia* root > *J. repens* root > *H. flavum* root > *E. crassipes* shoot > *Z. latifolia* shoot > *P. karka* shoot > *J. repens* shoot; Mn in the order of *P. perfoliatum* shoot > *P. perfoliatum* root > *I. aquatica* root > *E. crassipes* root > *H. flavum* shoot > *I. aquatica* shoot > *C. esculenta* shoot > *O. javanica* shoot > *H. flavum* root > *J. repens* root > *E. crassipes* shoot > *O. javanica* root > *C. esculenta* root > *Oenanthe sp.* root > *Oenanthe sp.* shoot > *Z. latifolia* root > *J. repens* shoot > *Z. latifolia* shoot > *P. karka* shoot > *P. karka* root; Zn in the order of *J. repens* root > *Oenanthe sp.* root > *Oenanthe sp.* shoot > *J. repens* shoot > *P. karka* shoot > *C. esculenta* root > *H. flavum* root > *P. karka* root > *O. javanica* root > *E. crassipes* root > *C. esculenta* shoot > *I. aquatica* root > *O. javanica* shoot > *P. perfoliatum* shoot > *H. flavum* shoot > *Z. latifolia* root > *P. perfoliatum* root > *I. aquatica* shoot > *Z. latifolia* shoot > *E. crassipes* shoot; and finally, Fe in the order of *I. aquatica* root > *P. perfoliatum* root > *Z. latifolia* root > *C. esculenta* root > *J. repens* root > *O. javanica* root > *Oenanthe sp.* root > *I. aquatica* shoot > *P. perfoliatum* shoot > *O. javanica* shoot > *H. flavum* shoot > *H. flavum* root > *C. esculenta* shoot > *J. repens* shoot > *Oenanthe sp.* shoot > *E. crassipes* root > *P. karka* root > *Z. latifolia* shoot > *P. karka* shoot > *E. crassipes* shoot. Average BAF values of total plant tissues including both shoots and roots revealed that among the plant samples collected, *C. esculenta* was the best accumulator of the nutrients TP, K, and Ca; *I. aquatica* was the best accumulator of

TN and Fe; *P. perfoliatum* was the most efficient accumulator of heavy metals Cu and Mn; *J. repens* had the greatest accumulative capacity for Mg; and Zn was most efficiently accumulated in *Oenanthe sp.* from the surrounding lake water (Fig. 3).

Table 5
BAF (plant/water) for nutrients and heavy metals in samples of macrophyte species from the Loktak Lake

Plant	Plant part	Nutrient			Heavy metal					
		TP	TN	K	Ca	Mg	Cu	Mn	Zn	Fe
<i>P. karka</i>	Shoot	157.48	31695.39	32028.17	3.29	27.68	428.71	799.86	6649.61	487.09
	Root	164.37	18008.75	21091.55	1.77	19.94	1923.76	418.61	5529.92	1524.30
<i>Z. latifolia</i>	Shoot	403.49	32879.29	40938.89	2.94	25.40	484.86	3063.65	2424.57	1004.66
	Root	359.89	24330.67	14383.33	8.47	35.82	1400.46	4185.09	4301.72	14097.72
<i>H. flavum</i>	Shoot	542.72	35551.38	49450.29	102.23	56.66	4165.45	16948.49	4505.17	2567.14
	Root	460.89	19092.41	34251.46	26.94	56.95	853.40	11414.60	5697.05	2543.76
<i>P. perfoliatum</i>	Shoot	159.97	36868.09	22052.63	349.34	57.17	2977.49	27988.87	4553.51	5564.13
	Root	204.84	30284.51	16362.57	203.22	58.83	8957.07	26735.52	3792.99	15021.52
<i>I. aquatica</i>	Shoot	505.77	47401.83	21011.70	94.30	56.78	2317.28	15004.83	2448.71	7071.04
	Root	497.85	57935.57	15456.14	48.10	55.55	2945.55	23877.52	4808.86	15098.32
<i>Oenanthe sp.</i>	Shoot	157.48	22330.85	51514.08	592.53	55.79	1660.89	4292.62	6944.09	1544.30
	Root	247.01	25212.25	45246.48	318.72	58.54	4047.03	4820.50	7885.04	9345.36
<i>O. javanica</i>	Shoot	468.81	36868.09	54561.40	600.88	57.71	2939.79	14489.00	4766.05	3091.41
	Root	413.38	23700.92	33994.15	133.21	57.32	2209.95	9534.43	5259.41	10467.14
<i>J. repens</i>	Shoot	269.96	30254.70	29211.27	567.22	58.51	350.00	3991.00	6779.53	1983.31
	Root	304.40	43941.34	18774.65	351.61	58.77	1161.88	11068.53	7969.29	11671.85
<i>E. crassipes</i>	Shoot	94.70	4410.10	8479.20	832.02	58.70	558.09	10142.31	2142.81	298.99
	Root	85.50	3328.38	4777.58	376.12	57.68	2137.50	19287.51	5171.26	1529.68
<i>C. esculenta</i>	Shoot	598.16	47401.83	98467.84	673.77	56.77	3493.72	14964.89	5141.70	2100.89
	Root	450.33	12508.82	34011.70	661.97	57.09	1680.10	7402.97	6051.29	13421.88

Table 6
BAF (plant/sediment) for nutrients and heavy metals in samples of macrophyte species from the Loktak Lake

Plant	Plant part	Nutrient					Heavy metal			
		TP	TN	K	Ca	Mg	Cu	Mn	Zn	Fe
<i>P. karka</i>	Shoot	5.58	1.87	2.57	0.36	0.95	1.29	0.55	1.42	0.08
	Root	5.82	1.06	1.69	0.20	0.69	5.80	0.29	1.18	0.24
<i>Z. latifolia</i>	Shoot	6.10	2.94	4.23	0.32	0.86	1.89	1.07	1.08	0.11
	Root	5.44	2.18	1.49	0.91	1.22	5.47	1.46	1.92	1.48
<i>H. flavum</i>	Shoot	38.79	3.86	4.76	9.12	1.95	8.31	4.92	1.81	0.30
	Root	32.94	2.07	3.30	2.40	1.96	1.70	3.31	2.29	0.29
<i>P. perfoliatum</i>	Shoot	11.43	4.00	2.12	31.18	1.97	5.94	8.12	1.83	0.64
	Root	14.64	3.29	1.57	18.14	2.03	17.87	7.76	1.53	1.73
<i>I. aquatica</i>	Shoot	36.15	5.14	2.02	8.42	1.96	4.62	4.35	0.99	0.81
	Root	35.58	6.29	1.49	4.29	1.92	5.88	6.93	1.94	1.74
<i>Oenanthe sp.</i>	Shoot	5.58	1.32	4.14	65.32	1.92	5.01	2.97	1.48	0.24
	Root	8.75	1.49	3.63	35.14	2.02	12.21	3.34	1.69	1.46
<i>O. javanica</i>	Shoot	33.51	4.00	5.25	53.62	1.99	5.86	4.20	1.92	0.36
	Root	29.55	2.57	3.27	11.89	1.98	4.41	2.77	2.12	1.21
<i>J. repens</i>	Shoot	9.56	1.79	2.35	62.53	2.01	1.06	2.76	1.45	0.31
	Root	10.78	2.60	1.51	38.76	2.02	3.51	7.66	1.70	1.82
<i>E. crassipes</i>	Shoot	8.35	3.53	2.61	77.32	2.04	2.45	2.89	1.15	0.34
	Root	7.54	2.67	1.47	34.95	2.01	9.38	5.49	2.77	1.76
<i>C. esculenta</i>	Shoot	42.75	5.14	9.48	60.13	1.96	6.97	4.34	2.07	0.24
	Root	32.19	1.36	3.27	59.08	1.97	3.35	2.15	2.44	1.55

Considering sediments as the external environment, the overall BAF values were found to be smaller for all the nutrients and heavy metals under consideration in all the macrophyte species as compared to lake water as the external medium, with some of the species also exhibiting BAF < 1, indicating that they could not efficiently accumulate certain elements from the lake sediments, as shown in Table 6. BAF values of the plants in this case for nutrients ranged between 5.44–42.75 for TP, 1.06–6.29 for TN, 1.47–9.48 for K, 0.2–77.32 for Ca, and 0.69–2.04 for Mg. Whereas, BAFs for heavy metals ranged between 1.06–17.87 for Cu, 0.29–8.12 for Mn, 0.99–2.77 for Zn, and 0.08–1.82 for Fe. The efficiency to accumulate TP by the plant tissues from the lake sediments was in the order of *C. esculenta* shoot > *H. flavum* shoot > *I. aquatica* shoot > *I. aquatica* root > *O. javanica* shoot > *H. flavum* root > *C. esculenta* root > *O. javanica* root > *P. perfoliatum* root > *P. perfoliatum* shoot > *J. repens* root > *J. repens* shoot > *Oenanthe sp.* root > *E. crassipes* shoot > *E. crassipes* root > *Z. latifolia* shoot > *P. karka* root > *P. karka* shoot = *Oenanthe sp.* shoot > *Z. latifolia* root; that of TN was in the order of *I. aquatica* root > *I. aquatica* shoot = *C. esculenta* shoot > *O. javanica* shoot = *P. perfoliatum* shoot > *H. flavum* shoot > *E. crassipes* shoot > *P. perfoliatum* root > *Z. latifolia* shoot > *E. crassipes* root > *J. repens* root > *O. javanica* root > *Z. latifolia* root > *H. flavum* root > *P. karka* shoot > *J. repens* shoot > *Oenanthe sp.* root > *C. esculenta* root > *Oenanthe sp.* shoot > *P. karka* root; K was in the order of *C. esculenta* shoot > *O. javanica* shoot > *H. flavum* shoot > *Z. latifolia* shoot > *Oenanthe sp.* shoot > *Oenanthe sp.* root > *H. flavum* root > *C. esculenta* root > *O. javanica* root > *E. crassipes* shoot > *P. karka* shoot > *J. repens* shoot > *P. perfoliatum* shoot > *I. aquatica* shoot > *P. karka* root > *P. perfoliatum* root > *J. repens* root > *I. aquatica* root > *Z. latifolia* root > *E. crassipes* root; Ca was in the order of *E. crassipes* shoot > *Oenanthe sp.* shoot > *J. repens* shoot > *C. esculenta* shoot > *C. esculenta* root > *O. javanica* shoot > *J. repens* root > *Oenanthe sp.* root > *E. crassipes* root > *P. perfoliatum* shoot > *P. perfoliatum* root > *O. javanica* root > *H. flavum* shoot > *I. aquatica* shoot > *I. aquatica* root > *H. flavum* root > *Z. latifolia* root > *P. karka* shoot > *Z. latifolia* shoot > *P. karka* root; Mg was in the order of *E. crassipes* shoot > *P. perfoliatum*

root > *J. repens* root > *Oenanthe* sp. root > *J. repens* shoot > *E. crassipes* root > *O. javanica* shoot > *O. javanica* root > *P. perfoliatum* shoot > *C. esculenta* root > *H. flavum* root > *I. aquatica* shoot > *C. esculenta* shoot > *H. flavum* shoot > *Oenanthe* sp. shoot > *I. aquatica* root > *Z. latifolia* root > *P. karka* shoot > *Z. latifolia* shoot > *P. karka* root; Cu was in the order of *P. perfoliatum* root > *Oenanthe* sp. root > *E. crassipes* root > *H. flavum* shoot > *C. esculenta* shoot > *P. perfoliatum* shoot > *I. aquatica* root > *O. javanica* shoot > *P. karka* root > *Z. latifolia* root > *Oenanthe* sp. shoot > *I. aquatica* shoot > *O. javanica* root > *J. repens* root > *C. esculenta* root > *E. crassipes* shoot > *Z. latifolia* shoot > *H. flavum* root > *P. karka* shoot > *J. repens* shoot; Mn was in the order of *P. perfoliatum* shoot > *P. perfoliatum* root > *J. repens* root > *I. aquatica* root > *E. crassipes* root > *H. flavum* shoot > *I. aquatica* shoot > *C. esculenta* shoot > *O. javanica* shoot > *Oenanthe* sp. root > *H. flavum* root > *Oenanthe* sp. shoot > *E. crassipes* shoot > *O. javanica* root > *J. repens* shoot > *C. esculenta* root > *Z. latifolia* root > *Z. latifolia* shoot > *P. karka* shoot > *P. karka* root; Zn was in the order of *E. crassipes* root > *C. esculenta* root > *H. flavum* root > *O. javanica* root > *C. esculenta* shoot > *I. aquatica* root > *O. javanica* shoot > *Z. latifolia* root > *P. perfoliatum* shoot > *H. flavum* shoot > *J. repens* root > *Oenanthe* sp. root > *P. perfoliatum* root > *Oenanthe* sp. shoot > *J. repens* shoot > *P. karka* shoot > *P. karka* root > *E. crassipes* shoot > *Z. latifolia* shoot > *I. aquatica* shoot; and Fe was in the order of *J. repens* root > *E. crassipes* root > *I. aquatica* root > *P. perfoliatum* root > *C. esculenta* root > *Z. latifolia* root > *Oenanthe* sp. root > *O. javanica* root > *I. aquatica* shoot > *P. perfoliatum* shoot > *O. javanica* shoot > *E. crassipes* shoot > *J. repens* shoot > *H. flavum* shoot > *H. flavum* root > *C. esculenta* shoot > *Oenanthe* sp. shoot > *P. karka* root > *Z. latifolia* shoot > *P. karka* shoot. Bioaccumulative capacities of the plants from the lake sediments, based on average BAF values of total plant tissues including both shoot and roots revealed similar order of bioaccumulation efficiencies by the plants from water, with few minor variations. It was observed that *C. esculenta* was the most efficient accumulator of the nutrients TP, K, Ca, and heavy metal Zn; *I. aquatica* was the best accumulator of TN and Fe; *E. crassipes* was the most efficient accumulator of Mg; and *P. perfoliatum* was the best accumulator of heavy metals Cu and Mn (Fig. 3). The BAF values can also help in establishing the phytoremediation capacities of the plants as those with higher accumulative properties may be potentially used for phytoremediation in polluted aquatic ecosystems.

Translocation Factor (Tf)

The TFs for nutrients and heavy metals in the different macrophyte species are shown in Table 7 and Fig. 4 which represent the efficiencies of the plants to translocate the selected elements from their roots to shoots. *P. karka* exhibited TF values greater than 1 for TN (1.76), K (1.519), Ca (1.855), Mg (1.388), Mn (1.911), and Zn (1.202), indicating that the plant effectively translocates these elements from their roots to shoots (Baker and Brooks 1989; Jha et al. 2016). Similarly, *Z. latifolia* exhibited TF > 1 for TP (1.121), TN (1.351), and K (2.846). *H. flavum* had TF > 1 for TP (1.178), TN (1.862), K (1.444), Ca (3.795), Cu (4.881), Mn (1.485), and Fe (1.009). *P. perfoliatum* had TF > 1 for TN (1.217), K (1.348), Ca (1.719), Mn (1.047), and Zn (1.201). *I. aquatica* had TF > 1 for TP (1.016), K (1.359), Ca (1.961), and Mg (1.022). *Oenanthe* sp. had TF > 1 only for K (1.139) and Ca (1.859). *O. javanica* had TF > 1 for TP (1.134), TN (1.556), K (1.605), Ca (4.511), Mg (1.007), Cu (1.33), and Mn (1.52). *J. repens* had TF > 1 only for K (1.556) and Ca (1.613). *E. crassipes* exhibited TF > 1 for TP (1.108), TN (1.325), K (1.775), Ca (2.212), and Mg (1.018). And finally, *C. esculenta* showed TF > 1 for TP (1.328), TN (3.789), K (2.895), Ca (1.018), Cu (2.079), and Mn (2.021). Thus, these plants may be used for the extraction of those particular elements from contaminated aquatic environments as the elements will be effectively stored in their biomass which can subsequently be recovered and disposed appropriately. In particular, *P. karka* and *E. crassipes* which are found abundantly in the lake may play a major role in the phytoextraction of the particular nutrients and heavy metals from the lake water and sediments, aiding in control of eutrophication and metal contamination of the lake. The order of plant species with most effective translocation capacities have been given below:

Table 7
TF (shoot/root) for nutrients and heavy metals in samples of macrophyte species from the Loktak Lake

Plant	Nutrient					Heavy metal			
	TP	TN	K	Ca	Mg	Cu	Mn	Zn	Fe
<i>P. karka</i>	0.958	1.760	1.519	1.855	1.388	0.223	1.911	1.202	0.320
<i>Z. latifolia</i>	1.121	1.351	2.846	0.347	0.709	0.346	0.732	0.564	0.071
<i>H. flavum</i>	1.178	1.862	1.444	3.795	0.995	4.881	1.485	0.791	1.009
<i>P. perfoliatum</i>	0.781	1.217	1.348	1.719	0.972	0.332	1.047	1.201	0.370
<i>I. aquatica</i>	1.016	0.818	1.359	1.961	1.022	0.787	0.628	0.509	0.468
<i>Oenanthe sp.</i>	0.638	0.886	1.139	1.859	0.953	0.410	0.890	0.881	0.165
<i>O. javanica</i>	1.134	1.556	1.605	4.511	1.007	1.330	1.520	0.906	0.295
<i>J. repens</i>	0.887	0.689	1.556	1.613	0.996	0.301	0.361	0.851	0.170
<i>E. crassipes</i>	1.108	1.325	1.775	2.212	1.018	0.261	0.526	0.414	0.195
<i>C. esculenta</i>	1.328	3.789	2.895	1.018	0.994	2.079	2.021	0.850	0.157

1. TP: *C. esculenta* > *H. flavum* > *O. javanica* > *Z. latifolia* > *E. crassipes* > *I. aquatica* > *P. karka* > *J. repens* > *P. perfoliatum* > *Oenanthe sp.*
2. TN: *C. esculenta* > *H. flavum* > *P. karka* > *O. javanica* > *Z. latifolia* > *E. crassipes* > *P. perfoliatum* > *Oenanthe sp.* > *I. aquatica* > *J. repens*
3. K: *C. esculenta* > *Z. latifolia* > *E. crassipes* > *O. javanica* > *J. repens* > *P. karka* > *H. flavum* > *I. aquatica* > *P. perfoliatum* > *Oenanthe sp.*
4. Ca: *O. javanica* > *H. flavum* > *E. crassipes* > *I. aquatica* > *Oenanthe sp.* > *P. karka* > *P. perfoliatum* > *J. repens* > *C. esculenta* > *Z. latifolia*
5. Mg: *P. karka* > *I. aquatica* > *E. crassipes* > *O. javanica* > *J. repens* > *H. flavum* > *C. esculenta* > *P. perfoliatum* > *Oenanthe sp.* > *Z. latifolia*
6. Cu: *H. flavum* > *C. esculenta* > *O. javanica* > *I. aquatica* > *Oenanthe sp.* > *Z. latifolia* > *P. perfoliatum* > *J. repens* > *E. crassipes* > *P. karka*
7. Mn: *C. esculenta* > *P. karka* > *O. javanica* > *H. flavum* > *P. perfoliatum* > *Oenanthe sp.* > *Z. latifolia* > *I. aquatica* > *E. crassipes* > *J. repens*
8. Zn: *P. karka* > *P. perfoliatum* > *O. javanica* > *Oenanthe sp.* > *J. repens* > *C. esculenta* > *H. flavum* > *Z. latifolia* > *I. aquatica* > *J. repens*
9. Fe: *H. flavum* > *I. aquatica* > *P. perfoliatum* > *P. karka* > *O. javanica* > *E. crassipes* > *J. repens* > *Oenanthe sp.* > *C. esculenta* > *Z. latifolia*

Health Risk Assessment Of Edible Macrophytes

The health risks associated with the consumption of the edible macrophytes of the lake in terms of heavy metal contamination have been assessed on the basis of the THQs of the plant samples as well as the HI (USEPA 2012). The EDI, THQ, and HI values of the selected heavy metals through the consumption of the edible macrophyte species have been presented in Table 8. The EDI values for Cu were found to range from 0.01 mg/kg/day (*J. repens* shoot) to 0.244 mg/kg/day (*P. perfoliatum* root). EDI for Mn ranged from 0.051 mg/kg/day (*P. karka* root) to 1.344 mg/kg/day (*J. repens* root). Similarly, EDI for Zn ranged from 0.08 mg/kg/day (*Z. latifolia* shoot) to 0.234 mg/kg/day (*C. esculenta* root), and finally, EDI for Fe ranged from 0.105 mg/kg/day (*P. karka* shoot) to 2.518 mg/kg/day (*J. repens* root). All EDI values were found to be within the respective provisional upper tolerable daily intake (PTDI) values as specified by the Food and Drug Association (2001). PTDI values of Fe, Mn, Zn, and Cu are 45, 11, 40, and 10 mg/kg body weight/day, respectively (Food and Drug Association 2001; Meitei and Prasad 2016). THQs for Cu ranged from 0.253 to 6.11, in the order of *P. perfoliatum* root > *Oenanthe sp.* root > *H. flavum* shoot > *C. esculenta* shoot > *P. perfoliatum* shoot > *I. aquatica* root > *O. javanica* shoot > *I. aquatica* shoot > *O. javanica* root > *P. karka* root > *Oenanthe sp.* shoot > *C. esculenta* root > *Z. latifolia* root exhibiting THQ values greater than 1, thus indicating potential health effects to the exposed population due to Cu contamination in these plant

tissues. High concentrations of Cu in the human body exceeding safe limits can cause various health issues such as nausea, dizziness, gastrointestinal distress, vomiting, anaemia, damage to the liver and kidney, etc. (Nodberg et al. 2007; Bermudez et al. 2011; Kacholi and Sahu 2018; Ibrahim et al. 2021). Similarly, THQs for Mn ranged from 0.363 to 9.6, in the order of *J. repens* root > *P. perfoliatum* shoot > *P. perfoliatum* root > *I. aquatica* root > *H. flavum* shoot > *I. aquatica* shoot > *C. esculenta* shoot > *O. javanica* shoot > *Oenanthe sp.* root > *H. flavum* root > *Oenanthe sp.* shoot > *J. repens* shoot > *O. javanica* root > *C. esculenta* root > *Z. latifolia* root > *Z. latifolia* shoot exhibiting THQ values greater than 1, implying potential toxic effects due to Mn contamination resulting from consumption of these plants. THQ values for Zn ranged from 0.268 to 0.781, with none of the plants having THQs greater than 1, suggesting low to no risk of toxicological impacts on health due to presence of Zn. Finally, the THQs of Fe ranged from 0.15 to 3.597, in the order of *J. repens* root > *I. aquatica* root > *P. perfoliatum* root > *C. esculenta* root > *Z. latifolia* root > *Oenanthe sp.* root > *O. javanica* root > *I. aquatica* shoot > *P. perfoliatum* shoot exhibiting THQ values greater than 1 and signifies that consumption of these edible plants may potentially lead to adverse health impacts due to Fe. Generally, possible health impacts associated with excessive assimilation of Fe in the human body include siderosis in liver, heart, pituitary, pancreas, thyroid, and adrenal glands, as well as an upset stomach or constipation (Kacholi and Sahu 2018). The THQs of Mn have been found to be relatively higher than those of Cu, Zn, and Fe for most of the edible macrophyte species, with 8 out of the 9 edible plants exhibiting THQ > 1, signifying a greater threat to human health from the toxicological effects of Mn. The higher THQs for Mn in the plant tissues may also be associated with the corresponding higher BAF values, signifying greater potential health risk due to greater uptake or accumulation of the metal in the plant tissues. Although Mn is required for the plants and animals, high concentrations can result in damage to lungs and brain, and also lead to structural and reproductive problems in mammals (Flefel et al. 2020). Therefore, caution is to be taken when consuming edible plants that may accumulate Mn in large amounts in their tissues by avoiding regular or overconsumption of such plants. The hazard index (HI), representing the total effects of all the heavy metals under consideration to the exposed population, was found to be greater than 1 (ranging from 1.55–18.9) for all the edible plants indicating that long-term consumption of these edible macrophyte species by the dependent population may potentially cause undesirable health effects. HI was found to be highest in *P. perfoliatum*, indicating a potentially higher risk to health due to the combined effects of all the heavy metals if this edible macrophyte is consumed in higher quantities on a regular basis, and thereby possibly leading to long-term health effects to the exposed population. Graphical representations of the THQs of the plants for each heavy metal with reference to the threshold value have been presented in Figs. 5 (a), (b), (c), and (d), while that of HIs has been shown in Fig. 6. The THQs and HI finally signify that the dependent communities in the vicinity of Loktak Lake may have unwanted long-term health effects associated with one or more heavy metal contamination from the edible macrophytes growing within the lake if these plants have been consumed regularly in significant amounts. Thus, care should be taken in the future to avoid regular or excessive consumption of these plants by the local population to prevent unwanted toxic health effects associated with metal contamination.

Table 8
Estimated EDI, THQ, and HI values of different heavy metals through consumption of edible macrophytes of the Loktak Lake

Plant	Plant part	EDI (mg/kg/day)				THQ				HI
		Cu	Mn	Zn	Fe	Cu	Mn	Zn	Fe	
<i>P. karka</i>	Shoot	0.012	0.097	0.121	0.105	0.309	0.694	0.402	0.150	1.555
	Root	0.056	0.051	0.100	0.329	1.388	0.363	0.334	0.470	2.555
<i>Z. latifolia</i>	Shoot	0.015	0.156	0.080	0.145	0.378	1.116	0.268	0.207	1.968
	Root	0.044	0.213	0.143	2.030	1.090	1.525	0.475	2.900	5.990
<i>H. flavum</i>	Shoot	0.114	0.784	0.174	0.414	2.841	5.603	0.581	0.591	9.618
	Root	0.023	0.528	0.221	0.410	0.582	3.774	0.735	0.586	5.677
<i>P. perfoliatum</i>	Shoot	0.081	1.295	0.176	0.897	2.031	9.253	0.588	1.282	13.154
	Root	0.244	1.237	0.147	2.423	6.110	8.839	0.489	3.461	18.900
<i>I. aquatica</i>	Shoot	0.063	0.695	0.095	1.140	1.581	4.961	0.316	1.629	8.487
	Root	0.080	1.105	0.186	2.435	2.009	7.894	0.621	3.479	14.003
<i>Oenanthe sp.</i>	Shoot	0.048	0.521	0.126	0.333	1.198	3.723	0.420	0.476	5.817
	Root	0.117	0.585	0.143	2.016	2.920	4.181	0.477	2.880	10.457
<i>O. javanica</i>	Shoot	0.080	0.671	0.185	0.499	2.005	4.790	0.615	0.712	8.123
	Root	0.060	0.441	0.204	1.688	1.508	3.152	0.679	2.412	7.750
<i>J. repens</i>	Shoot	0.010	0.485	0.123	0.428	0.253	3.462	0.410	0.611	4.735
	Root	0.034	1.344	0.145	2.518	0.838	9.600	0.482	3.597	14.517
<i>C. esculenta</i>	Shoot	0.095	0.693	0.199	0.339	2.383	4.948	0.664	0.484	8.478
	Root	0.046	0.343	0.234	2.165	1.146	2.448	0.781	3.093	7.467

Correlation Analysis

The degree of linear association between the variables were assessed using Pearson correlation matrix for both water and sediment parameters of the lake (Table 9). The significant ($p < 0.05$) strong correlation were observed among some of the parameters for both water and sediments samples. Positive strong correlation between TP and TN ($r = +0.998$) in water indicates common sources of nutrient due to runoff from surrounding catchments. Similarly, the strong correlation between Fe and Cu ($r = +0.93$) and moderate correlation between Zn and Cu ($r = +0.646$), and Fe and Zn ($r = +0.687$) indicates the anthropogenic source from agricultural runoff, disposal of solid and sewage through runoff from the feeder streams of the catchments of the lake. Generally, the significant positive correlation highlights the dissolution of these elements that have their common anthropogenic origin which are basically due to uncontrolled inflow of untreated waste water from the numerous feeder streams and channels that pass through the urban landscapes and habitations. Moreover, significant strong correlation were also observed between the nutrients and heavy metals concentration in water (TP-Cu; TP-Fe; TN-Cu; TN-Zn; TN-Fe) and indicates the common anthropogenic sources. The sediment parameters also exhibits significant ($p < 0.05$) strong correlation between Zn and Cu ($r = +0.842$); Fe and Zn ($r = +0.863$); as well as moderate correlation between Fe and Cu ($r = +0.508$); Fe and Mn ($r = +0.677$) that have strong chance of common anthropogenic origin. The correlation matrix between nutrient and heavy metal concentration in the macrophyte samples has also been presented in Table 10. The correlation of nutrient and heavy metal in macrophytes exhibited random values with some few significant ($p \leq 0.05$) covariability between Mn and Mg ($r = +0.784$), and between Fe and Mn ($r = +0.725$) indicating strong affinity for bioaccumulation of these elements by the macrophytes which also observed in the Fig. 3.

Table 9
Correlation matrix of nutrients and heavy metals concentration in (a) water and (b) sediments samples of the Loktak Lake

	pH	EC	TP	TN	K	Ca	Mg	Cu	Mn	Zn	Fe
(a) Water											
pH	1										
EC	-0.983	1									
TP	-0.983	0.986	1								
TN	-0.976	0.990	0.998	1							
K	-0.958	0.983	0.992	0.997	1						
Ca	0.686	-0.796	-0.790	-0.823	-0.860	1					
Mg	-0.142	0.279	0.128	0.180	0.197	-0.427	1				
Cu	-0.877	0.879	0.943	0.937	0.945	-0.802	-0.098	1			
Mn	0.036	-0.210	-0.179	-0.235	-0.299	0.744	-0.574	-0.250	1		
Zn	-0.584	0.720	0.678	0.722	0.762	-0.972	0.621	0.646	-0.826	1	
Fe	-0.986	0.992	0.999	0.999	0.992	-0.791	0.162	0.930	-0.183	0.687	1
(b) Sediment											
pH	1										
EC	-0.435	1									
TP	0.246	0.610	1								
TN	-0.450	0.804	0.103	1							
K	-0.658	-0.378	-0.666	-0.289	1						
Ca	0.215	-0.444	-0.753	0.163	0.012	1					
Mg	0.704	0.325	0.668	0.223	-0.998	-0.019	1				
Cu	0.301	-0.843	-0.851	-0.358	0.306	0.850	-0.283	1			
Mn	-0.905	0.097	-0.335	0.027	0.879	-0.308	-0.898	-0.155	1		
Zn	-0.187	-0.763	-0.954	-0.377	0.771	0.588	-0.755	0.842	0.398	1	
Fe	-0.357	-0.666	-0.703	-0.572	0.938	0.099	-0.914	0.508	0.677	0.863	1
*Bold indicates significant value of r at $p < 0.05$											

Table 10
Correlation matrix of nutrient and heavy metal concentration in the samples of
macrophyte species of the lake

	TP	TN	K	Ca	Mg	Cu	Mn	Zn	Fe
TP	1								
TN	0.420	1							
K	0.521	-0.357	1						
Ca	-0.023	-0.153	0.429	1					
Mg	0.264	0.336	0.215	0.639	1				
Cu	-0.241	0.142	0.027	0.096	0.448	1			
Mn	-0.076	0.537	-0.317	0.320	0.784	0.630	1		
Zn	0.532	0.015	0.681	0.457	0.645	0.335	0.294	1	
Fe	0.062	0.671	-0.246	0.429	0.587	0.360	0.725	0.058	1
*Bold indicates significant value of r at $p < 0.05$									

Cluster Analysis

The hierarchical cluster analysis (HCA) was carried out to classify the macrophyte species with similar bioaccumulation efficiencies from both sediments and water of the lake ecosystem. The visual illustrations are shown in the figure, where different groups of macrophytes are identified based on their Q-mode clusters of samples and arbitrary similarity level of 50% were considered (Fig. 7a and 7b). The HCA revealed that the macrophyte species such as *P. perfoliatum* and *I. aquatica* are found to have highest hazards index (HI) (Fig. 6a & b) and similar bioaccumulation potential where as other species such as are as *P. karka*, *Z. latifolia*, *J. repens*, *H. flavum*, *O. javanica* and *Oenanthe sp.* are found to have similar bioaccumulation potential from water of the lake. Similarly, for sediments the HCA groups *P. perfoliatum*, *I. aquatica*, *O. javanica*, *H. flavum* in the same group having equivalent potential of bioaccumulation of heavy metals. The macrophyte species such as *Oenanthe sp.*, *E. crassipes*, *J. repens*, *C. esculenta* shows similar efficiency of bioaccumulation potential and shows moderate to high concentration of heavy metals in them. Thus, it can be seen that HCA classify three (3) different groups or clusters based on their efficiency of bioaccumulation of heavy metals from water and sediments when lake ecosystem is considered as the external environment.

Conclusion

Numerous edible plants and macrophyte species have been found growing within the water coverage area of Loktak Lake, which serve as a staple component in the diet of the local population residing within and around the lake. This study has revealed that there are significant potential health risks associated with the consumption of many of the plant species as they can accumulate heavy metals in their tissues effectively, and may gradually result in their biomagnification when these edible plants are consumed by people directly or indirectly. The present knowledgebase can serve as information regarding potential metal contamination and resulting long-term health effects on the exposed population. On the other hand, the macrophyte species showing high BAFs and TFs may have potential phytoremediation uses in contaminated aquatic ecosystems for the effective removal of undesirable heavy metals and nutrients, consequently, preserving the ecological health of the lake. Concentrations of nutrients and heavy metals in the lake sediments have also been found to be relatively high due to long-term accumulation from surrounding runoff and sedimentation processes. The lake water, on the other hand, has been found to have relatively low concentrations of most of the heavy metals, except for the presence of high levels of Fe in some sampling sites. The correlation studies reveals that the most common sources of these heavy metals in water and sediments are resulting from runoff from surrounding catchments through the feeder streams, agricultural runoff, disposal of untreated sewage and solid wastes due to human-centric activities. Although the present study is based on a few selected trace elements, further investigation is required to assess the influence of other trace elements for holistic investigation and ecological protection of the lake from metal contamination. The findings of the study may also help in the establishment of appropriate management strategies to control the discharge and accumulation of heavy metal contaminants into the lake water body. In addition,

the concerned stakeholders may create public awareness to caution the local population against overconsumption of these edible plants growing in the lake to prevent potential health risks.

Declarations

Acknowledgement

The authors thank the Department of Science and Technology (DST), Ministry of Science and Technology, India, for funding the research work under the DST-INSPIRE fellowship programme. The authors acknowledge ICAR RC NEH, Manipur Centre, for providing laboratory facilities for sample analysis. Authors also thank the local boatmen of Karang, Loktak, for their help in sample collection and fieldwork.

Funding

This research work was funded by the Department of Science and Technology (DST), Ministry of Science and Technology, India, under the DST-INSPIRE fellowship programme (DST/INSPIRE Fellowship/2018/IF180332).

Competing interests

The authors declare no conflict of interest.

Author contributions

Conceptualization: Wazir Alam, Ranu Jajo Laishram; Methodology: Tensubam Basanta Singh, Ranu Jajo Laishram; Field work, sample collection and analysis, investigation, and data interpretation: Ranu Jajo Laishram; Writing – original draft preparation: Ranu Jajo Laishram; Writing – review and editing: Wazir Alam, Ranu Jajo Laishram, Tensubam Basanta Singh; Funding acquisition: Ranu Jajo Laishram; Supervision: Wazir Alam, Tensubam Basanta Singh.

Ethical Approval

Ethical approval is “Not Applicable” for this manuscript.

Consent to Participate

Consent to participate is “Not Applicable” for this manuscript.

Consent to Publish

Consent to publish is “Not Applicable” for this manuscript.

Availability of data and materials

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figures

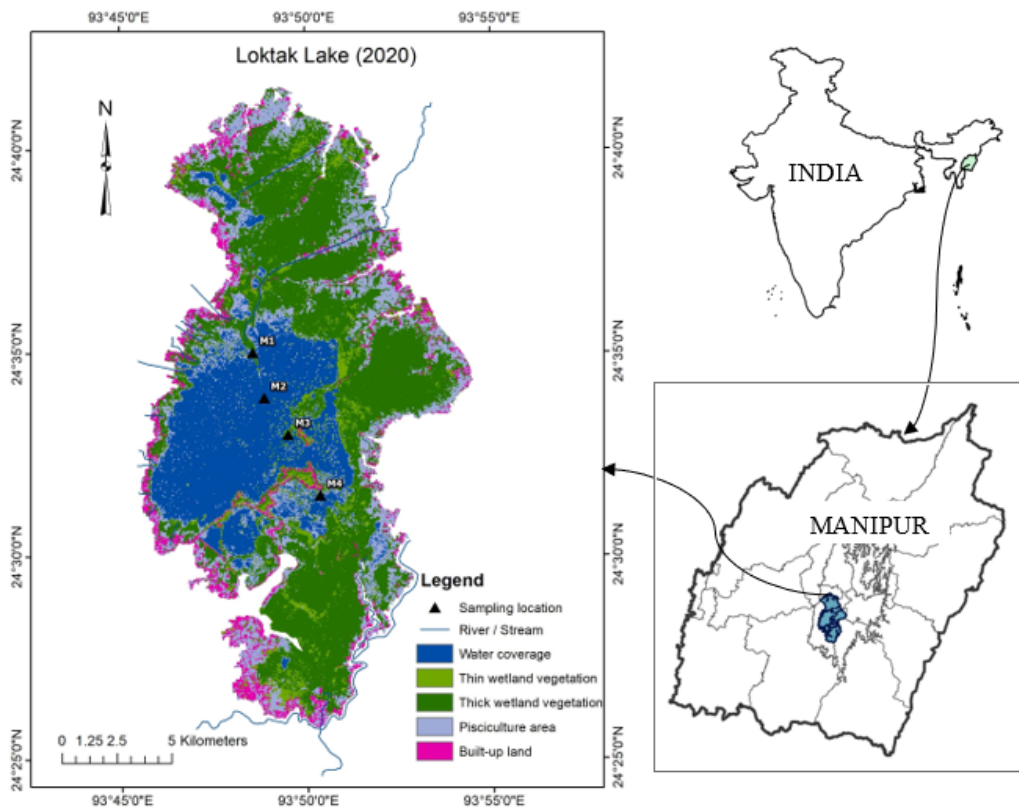


Figure 1

Map of study area with sampling locations

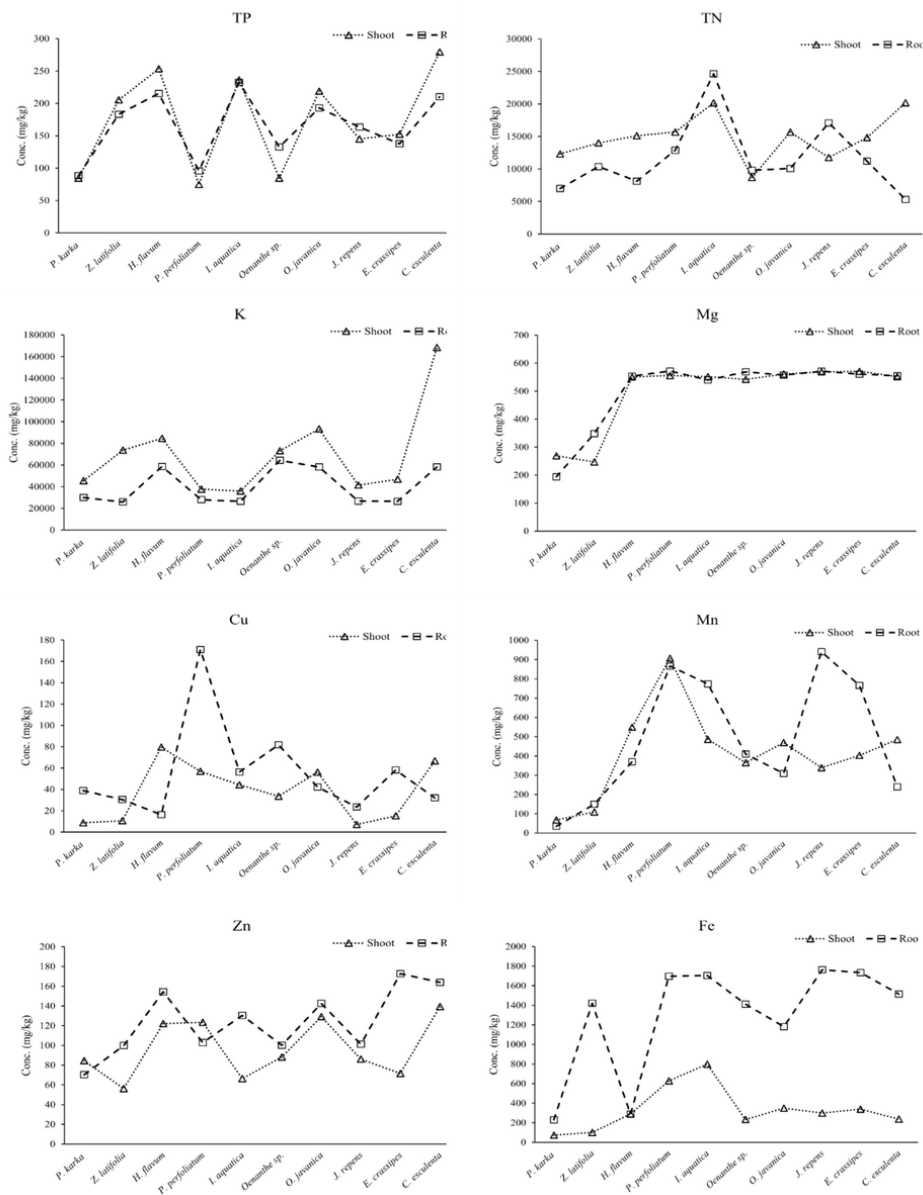


Figure 2

Concentrations of nutrients and heavy metals in the macrophyte species

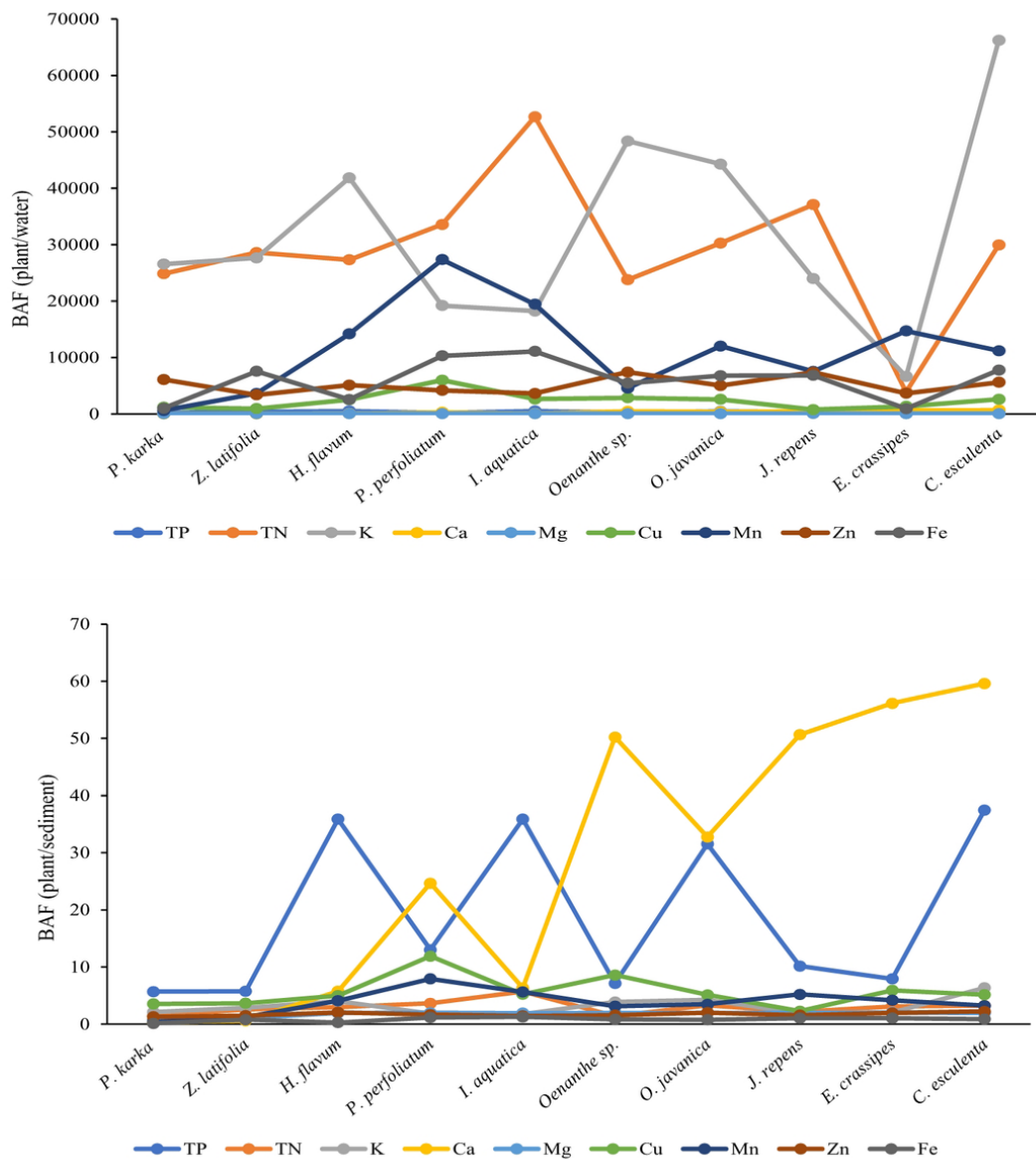


Figure 3

BAFs for nutrients and heavy metals in the macrophytes

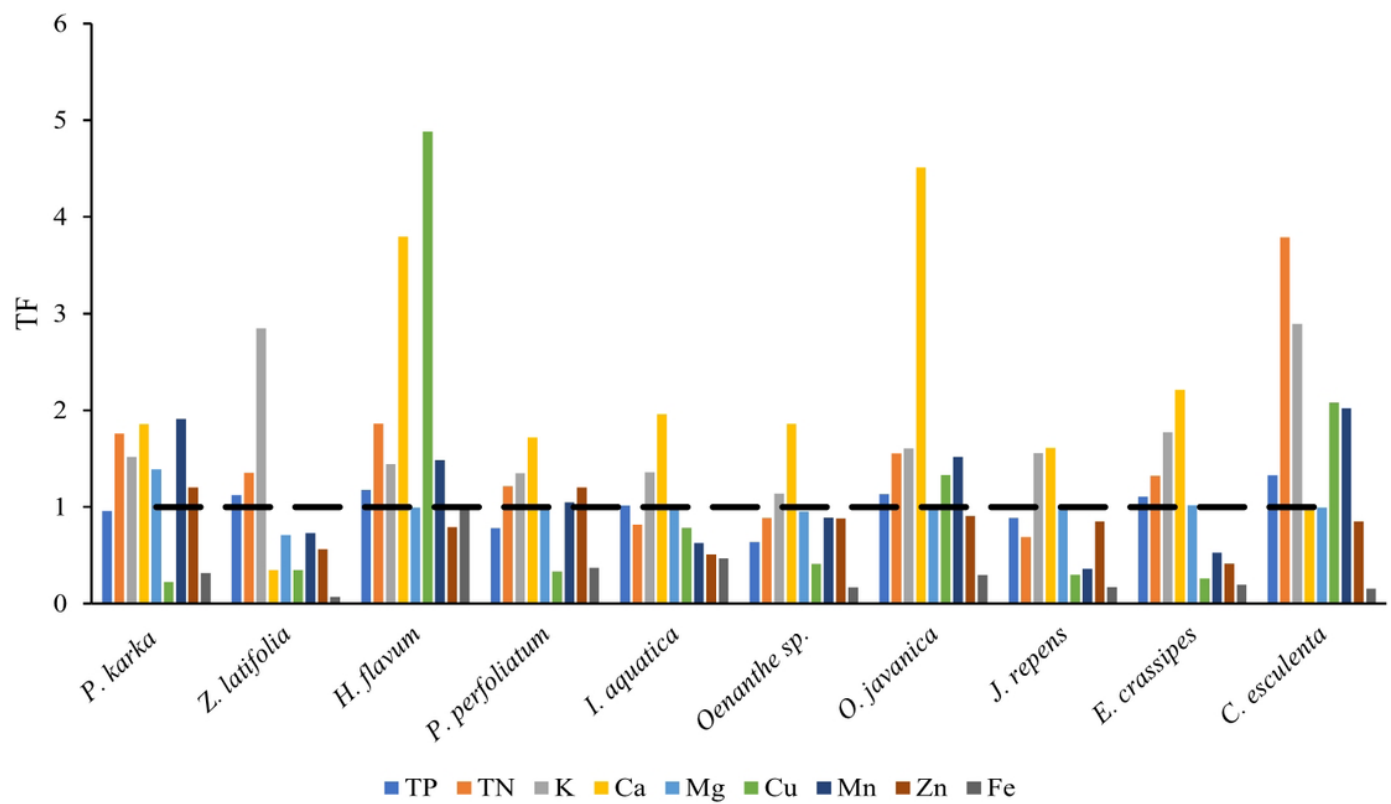
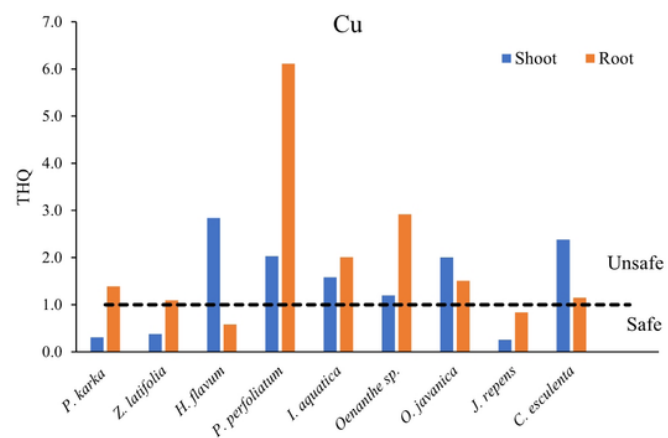
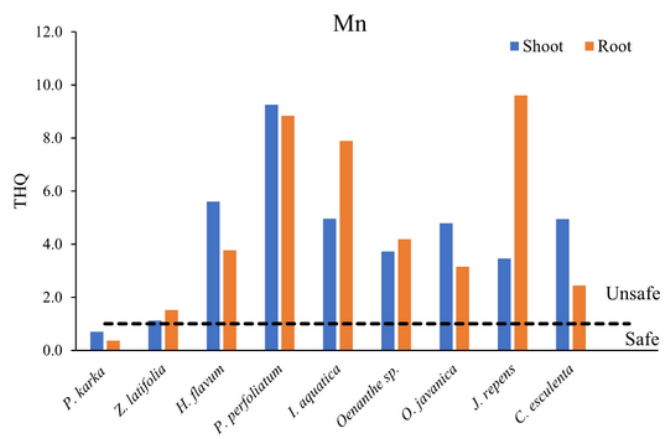


Figure 4

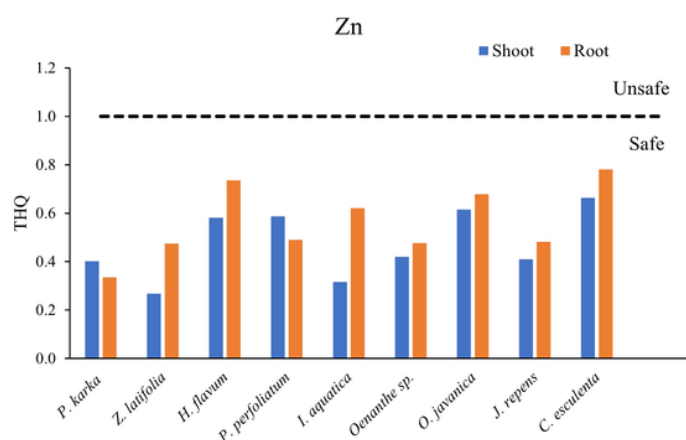
TFs for nutrients and heavy metals in the macrophytes



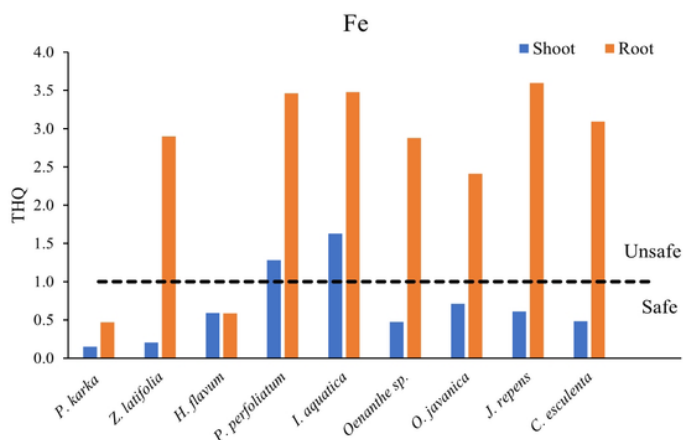
(a)



(b)



(c)



(d)

Figure 5

Target hazard quotients of the edible macrophytes for (a) Cu, (b) Mn, (c) Zn, and (d) Fe

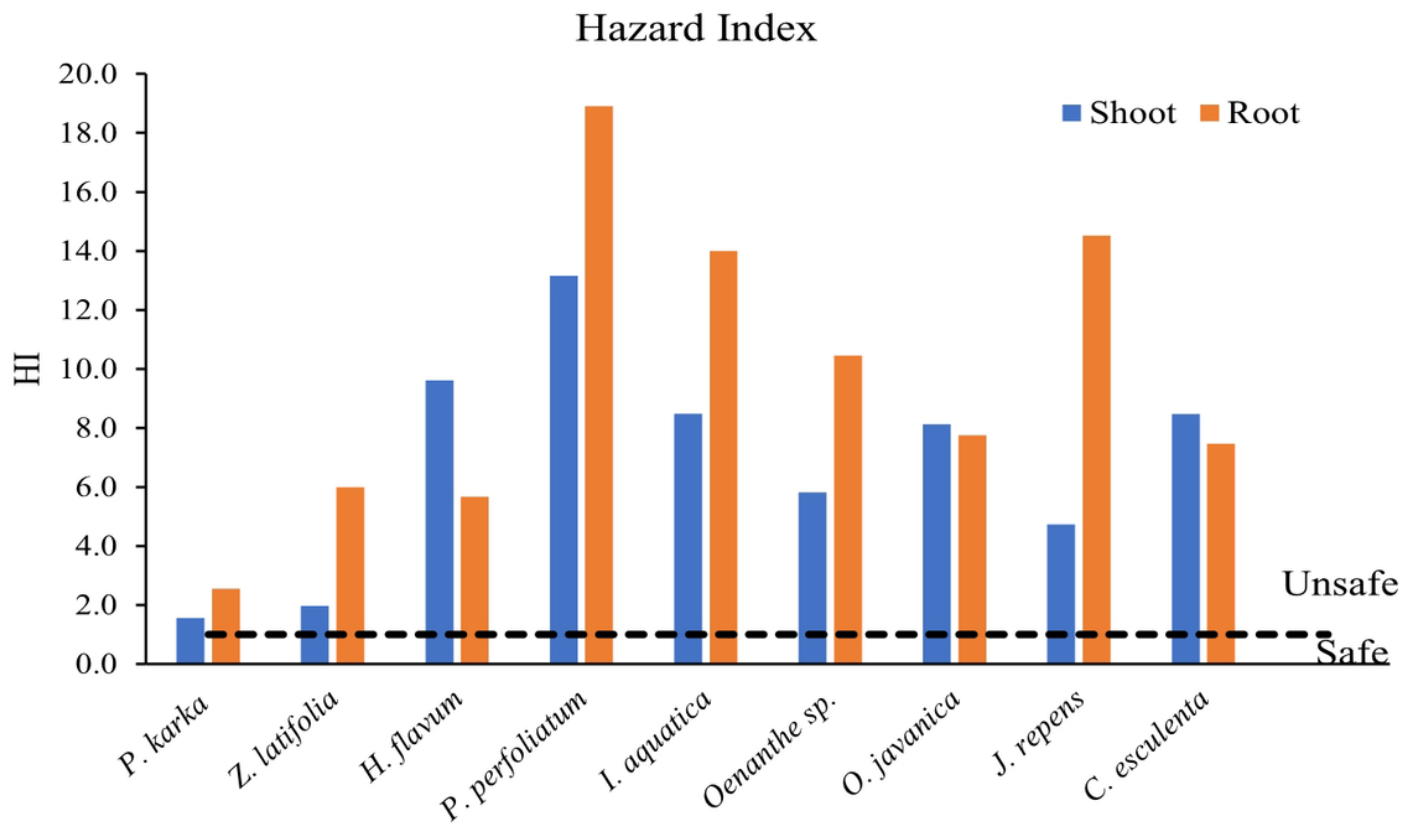
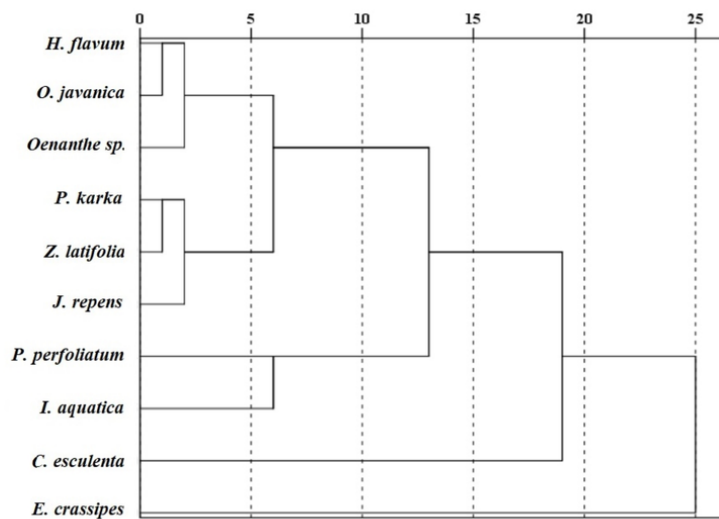
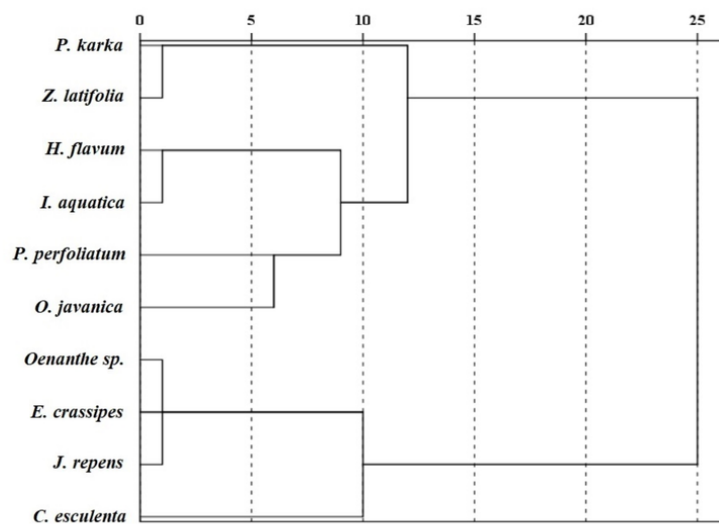


Figure 6

Hazard index signifying cumulative effects of all heavy metals through the consumption of the edible macrophytes



(a)



(b)

Figure 7

Dendrogram based on hierarchical cluster analysis showing the macrophyte species exhibiting similar bioaccumulation efficiencies from (a) lake water and (b) sediments