



# Heavy Metal Removal Capacity of Dominant Species in Wetland Plant Community—A Case Study of East Dongting Lake in China

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## Abstract

Wetlands, as one of the ecosystems with the richest biodiversity globally, play an irreplaceable role in maintaining ecological balance and biodiversity conservation. However, the East Dongting Lake wetland in China faces severe soil heavy metal pollution due to long-term human activities (such as industrial emissions and agricultural non-point source pollution) and natural processes. Contaminants such as arsenic (As) and cadmium (Cd) have accumulated over time, posing threats to the wetland's ecological security. This study targeted three typical plant communities in the East Dongting Lake wetland—*Miscanthus sacchariflorus* community, *Carex* community, and *Persicaria* community. Through field sampling, laboratory analysis, and Detrended Canonical Correspondence Analysis (DCA), it systematically evaluated the bioconcentration factor (BCF) of plant communities for heavy metals and their response to soil physicochemical properties. The research objectives included: a) identifying the characteristics of soil heavy metal pollution; b) quantifying the BCF of different plant communities; c) analyzing the correlation between biodiversity and heavy metal contents.

**Keywords:** East Dongting Lake wetland; Soil heavy metal pollution; Bioremediation; Plant community; Ecological restoration materials.

Received: 21 May 2025; Revised: 27 June 2025; Accepted: 06 July 2025

Article type: Research article.

## 1. Introduction

The bioaccumulation and toxicity of heavy metals pose severe threats to the ecological security of global lakeside wetlands.<sup>[1,2]</sup> Their long-term accumulation may transfer risks through the 'soil-plant-animal' food chain, inducing the decline of wetland biodiversity and human exposure health risks. For instance, Kumar *et al.* revealed that groundwater contamination with Fe and Cu in Jhunjhunu, India, exceeded safety limits, leading to cardiovascular diseases, methemoglobinemia, and respiratory disorders.<sup>[3]</sup> This highlights the urgency of addressing heavy metal pollution in wetland ecosystems. As the only international important wetland in the middle reaches of the Yangtze River,<sup>[4]</sup> the East

Dongting Lake wetland has soil arsenic (As, 88.7 mg/kg) and cadmium (Cd, 0.99 mg/kg) concentrations that are 6.3 times and 9.9 times higher than the background values of Hunan Province, respectively, and are increasing at annual rates of 3.2% and 2.5%. It has become one of the most severely heavy metal-polluted lakeside wetlands in the Yangtze River Basin (Table 1). Compared with Poyang Lake (dominated by nitrogen and phosphorus pollution) and Taihu Lake (frequent cyanobacterial blooms), this region faces unique triple stresses of "As/Cd composite pollution + seasonal flooding + acidic deposition", with governance challenges highly representative of similar wetlands globally.

Lakeside wetlands, as transition zones between land and water, are vulnerable to dual *impacts* of pollutant inputs and hydrological fluctuations on their ecosystem functions. Globally, lakeside wetland pollution is predominantly characterized by nitrogen-phosphorus (N/P) eutrophication (*e.g.*, total nitrogen in Poyang Lake exceeds Class III surface water standards by 1.8×), while East Dongting Lake exhibits unique As/Cd compound pollution (As: 88.7 mg/kg, 3.5× above the national standard; Cd: 0.99 mg/kg, 3.3× above the national standard), as revealed by the 2023 systematic sampling and analysis of its wetland surface soil.

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**Table 1:** Comparison of pollution characteristics between East Dongting Lake and similar lakeside wetlands.

Wetland name	Pollutant types	Key concentrations & exceedance	Ecological stressors	Remediation challenges
East Dongting Lake	As/Cd composite	As: 88.7 mg/kg (6.3× BG, 3.5× GB)	Seasonal flooding	Speciation shifts with flooding
		Cd: 0.99 mg/kg (9.9× BG, 3.3× GB)	Acid rain (pH 5.2)	Dual-functional plant scarcity
Poyang Lake	N/P eutrophication	TN: 2.8 mg/L (1.8× Class III)	Long flooding (>8 mo)	Declining submerged plants
		TP: 0.12 mg/L (2.4× standard)	Substrate disturbance	High microbial tech cost
Taihu Lake	Cyanotoxins/organics	Permanganate: 8.5 mg/L (70%× Class II)	Eutrophication + warming	Incomplete toxin degradation
		Microcystin: 0.8 µg/L (1.6× WHO)	Shipping pollution	Climate resilience gaps

Data Sources: China Wetland Ecological Environment Quality Report,<sup>[5]</sup> Yangtze River Basin Ecological Environment Bulletin Reproduced from.<sup>[6]</sup> Notes: BG = Hunan Province background value; GB = GB 15618 screening value.

This regional variation in pollution types is closely linked to mining activities (e.g., Shimen Realgar Mine in Hunan) and acidic soil backgrounds.

East Dongting Lake's ecological stressors are distinct:

- Seasonal flooding cycles (1–6 months) induce frequent fluctuations in soil redox conditions, promoting As/Cd speciation transformation (e.g., reduction of As (V) to As (III)) and mobility.
- Acid rain input (annual pH 5.2) exacerbates soil acidification, enhancing heavy metal bioavailability.

This synergistic stress of "composite heavy metal pollution + seasonal flooding + acidic deposition" is extremely rare in global lakeside wetlands, with sporadic records only in wetlands of the East Asian Circum-Pacific metallogenic belt (e.g., Ashio Copper Mine, Japan; Tongling Mining Area, China) (comprising <3% of global similar studies, Web of Science search). Compared to mine-polluted wetlands in Europe and America dominated by single heavy metals (e.g., Cd pollution in Germany's Ruhr Area), East Dongting Lake's "triple stress" presents higher governance complexity due to hydrological-chemical coupling processes driven by monsoon climates. However, 90% of current international remediation research focuses on N/P pollution or single heavy metal remediation (e.g., reviews in *Phytoremediation Journal* over the past five years), leaving a gap in mechanistic understanding and technical adaptation for coupled stresses in this region. East Dongting Lake's uniqueness provides a natural laboratory to reveal synergistic mechanisms of heavy metals-hydrology-acidification.<sup>[7]</sup> For example, flooding cycles increase exchangeable Cd proportions by 40–60% via soil Eh value changes ( $\pm 200$  mV), while acid rain further lowers soil pH, increasing As dissolution rates by 2–3×.

This study targeted three typical plant communities

(*Miscanthus sacchariflorus*, *Carex*, and *Persicaria*) in East Dongting Lake, using a multidisciplinary integrated approach to:

1. Quantify community diversity and pollution response: Based on standardized surveys of 1,800 quadrats,<sup>[8]</sup> establish an evaluation system with six diversity indicators to analyze the structural response patterns of dominant communities to heavy metal stress.

2. Analyze pollution characteristics and driving factors: Combine ICP-AES determination of eight heavy metals and 12 physicochemical parameters to clarify the spatial patterns of As/Cd composite pollution and its correlation with human activities (e.g., industrial emissions contribution rate >60%).

3. Screen efficient remediation plants and community configurations: Establish a hierarchical screening standard of "BCF>0.8" based on root BCF analysis to identify hyperaccumulating species (e.g., *Persicaria*) and specific enrichment groups (e.g., *Carex*), and optimize community configurations to enhance multi-metal synergistic remediation efficiency.

4. Reveal vegetation-environment interaction mechanisms: Use Detrended Canonical Correspondence Analysis (DCA) to quantify the driving effects of 20 environmental factors on community distribution and construct a cascade response model of "soil physicochemical properties - heavy metal activity - plant enrichment".

The essence of the advancement lies in the paradigm upgrade from conventional 'single material adsorption' strategies—such as Bhat *et al.* using Jungle Geranium leaf powder (JGLP) to remove single-component chromium (Cr VI) from wastewater, optimizing conditions at pH=2 and 303 K with Langmuir isotherm characterization to 'ecosystem function restoration'.<sup>[9]</sup> Unlike JGLP's single-pollutant focus

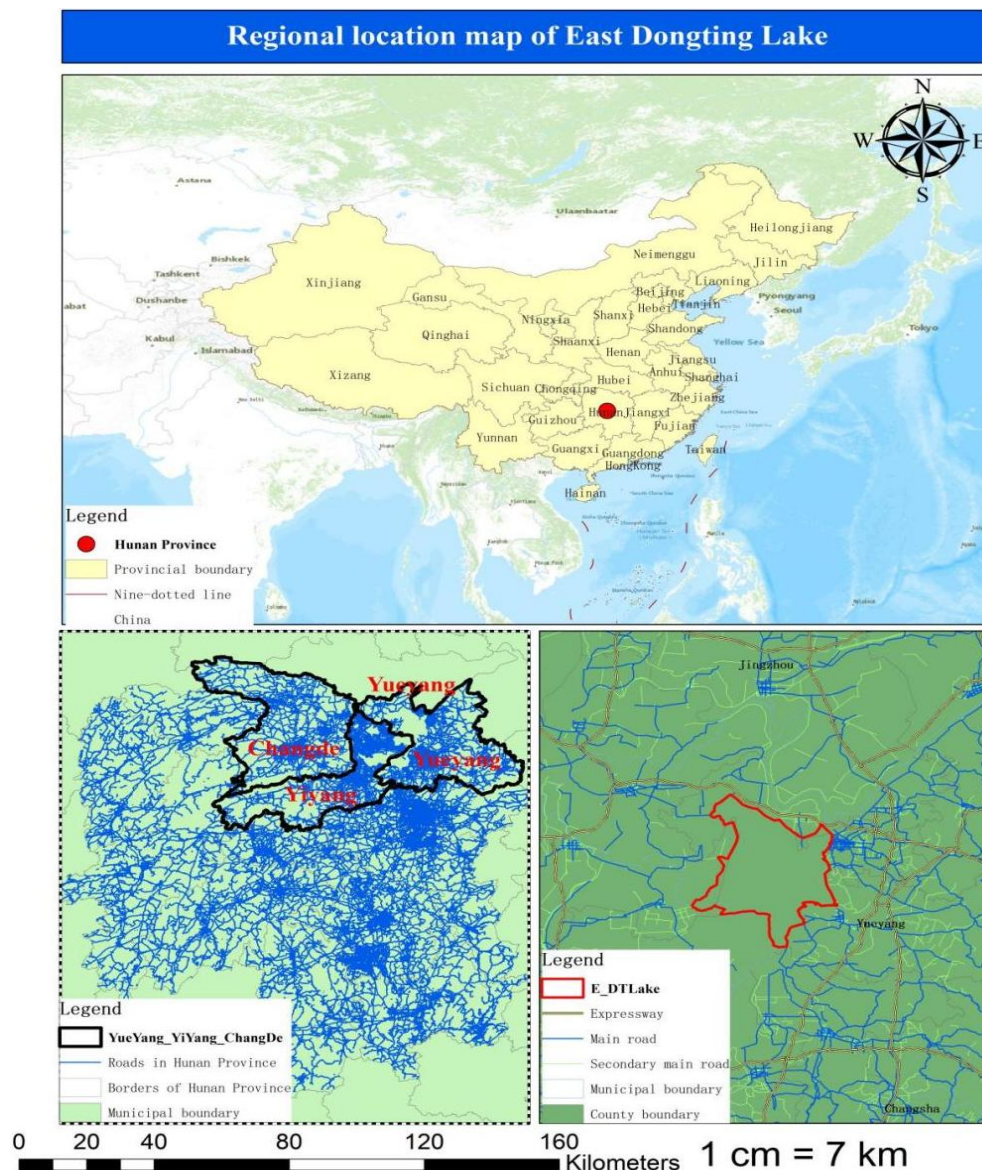


Fig. 1: Location of wetland areas in Dongting Lake area.

(71% Cr VI removal), this study integrates multi-metal pollution characteristics (As/Cd composite stress), community ecological processes (dominant plant distribution patterns), and environmental factor regulation (seasonal flooding impacts), offering a scientifically rigorous and practically viable solution for wetland remediation.

## 2. Materials and methods

### 2.1 Study area

East Dongting Lake (112°43′–113°15′E, 28°59′–29°38′N), located in Hunan Province (Fig. 1), is the largest lake in the Dongting Lake Basin with a total area of 1,650 km<sup>2</sup>. It plays a critical role in flood regulation in the middle reaches of the Yangtze River, species protection, and biodiversity maintenance.<sup>[10]</sup> The region has a subtropical monsoon climate, with an average annual temperature of 16–17 °C, annual precipitation of 1,000–1,450 mm (with significant interannual variation), a frost-free period of 230–240 days, sunshine hours

of 1,400–2,200 hours, and total solar radiation of 418–456 kJ/cm<sup>2</sup>. With distinct seasons and concentrated rainfall, its unique hydrological and climatic conditions have formed a typical lakeside wetland ecosystem.

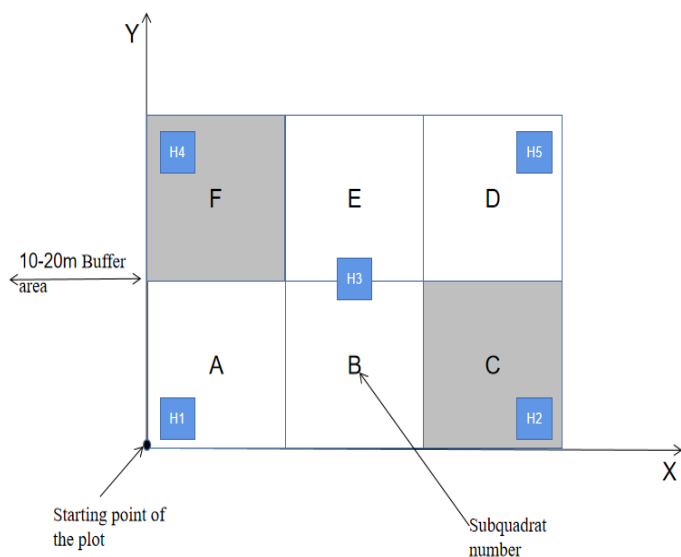
### 2.2 Preliminary processing and data collection

Data mapping of East Dongting Lake was conducted using the Landsat Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), with DEM (Digital Elevation Model) files sourced from the Geospatial Data Cloud. The national land use classification standard was adopted.<sup>[11]</sup> Based on a comprehensive survey and analysis of vegetation and soil in the wetland area, land use types in Dongting Lake were categorized into: I. Construction Land, II. Agricultural Dry Land, III. Paddy Field, IV. Forest Land, V. Reed Bed, VI. Riverbed, VII. Beach, VIII. Water Area. Detailed wetland vegetation surveys and soil sampling were carried out accordingly. Supporting data included land cover maps (ESA

CCI-LC) and 1:10,000 topographic maps.

### 2.2.1 Plot survey methodology

Vegetation surveys were conducted following the "Main Content, Methods, and Technical Specifications for Plant Community Catalogs". Specifically, over the past two years, the sample size was expanded to 1,800 plant quadrats at 180 sampling points, ensuring a robust dataset for analysis. Plant community surveys referenced the Wetland Ecological Monitoring Technical Regulations.<sup>[12]</sup> For the vertical stratification characteristics of wetland plants, 20m×30m composite quadrats were established (covering tree, shrub, and herb layers), with 10m×10m sub quadrats (2 replicates) for the shrub layer and 5m×5m sub quadrats (5 replicates) for the herb layer. A spacing of 10–20m between quadrats was maintained to avoid edge effects and ensure the integrity of community structure data [Fig. 2](#).



**Fig. 2:** Setting and numbering of wetland samples in Dongting Lake.

### 2.2.2 Selection and calculation of diversity indices

In adherence to the Standards for Plant Community Diversity Measurement,<sup>[6]</sup> this study established a three-dimensional evaluation system, employing a multi-index combination strategy to attain a refined characterization of community structure:

- Richness dimension

Patrick Index ( $(D_p = S)$ , where  $S$  = number of species;<sup>[13]</sup> directly quantifies absolute species richness.

Menhinick Index ( $(D_M = S / \ln N)$ , where  $N$  = total number of individuals;<sup>[14]</sup> eliminates sample size bias via logarithmic standardization, suitable for comparing quadrats of different areas.

- Evenness-dominance dimension

Shannon-Wiener Index ( $(H' = -\sum p_i \ln p_i)$ , where  $(p_i)$  = relative abundance; Shannon, 1948) amplifies rare species' weights through information entropy.

Simpson Index ( $(D_s = 1 - \sum p_i^2)$ ;<sup>[15]</sup> focuses on quantifying

dominant species' dominance, forming a complementary "diversity-dominance" evaluation framework.

- Index selection

Following the four-dimensional model proposed by Mason *et al.*<sup>[16]</sup> spatial scale effects were corrected via the combination of  $(D_p)$  and  $(D_M)$ . Multidimensional decomposition of community structure was achieved by integrating logarithmic-square transformation differences between  $(H')$  and  $(D_s)$ . All indices were calculated using the vegan package in R software,<sup>[17]</sup> with diversity analysis functions (diversity, dominance), based on field survey data from 1,800 quadrats. Data processing complied with quality control requirements of the Technical Specifications for Biodiversity Monitoring Specific formulas and ecological meanings are listed in [Table 2](#).<sup>[18]</sup>

**Table 2:** Formulas and significance of diversity indices.

No.	Diversity index	Formula for the calculation	Significance of calculation
1	Patrick abundance Index	$D_p = N$	The larger the $D_p$ , the greater the diversity. <sup>[13]</sup>
2	Menhinick Richness Index	$D_{Menhinick} = \frac{S}{\sqrt{N}}$	The larger the $D_{Menhinick}$ , the greater the diversity. <sup>[14]</sup>
3	Simpson index	$D_s = 1 - \sum_{i=1}^s p_i^2$	The closer $D_s$ is to 1, the lower the diversity. <sup>[15]</sup>
4	Shannon-Wiener index	$H = -\sum p_i \log p_i$	The larger the $H$ , the greater the diversity. <sup>[19]</sup>

In the diversity index calculation formulas, each symbol has a specific ecological meaning (see [Table 2](#) for details):  $S$  represents the total number of species in a quadrat, used in the Patrick Index ( $(D_p=S)$ ) to directly reflect species richness in the community.  $N$  denotes the total number of individuals of all species in the quadrat. In the Menhinick Index ( $(D_M=S / \ln N)$ ), it combines with the species number ( $S$ ) to eliminate sample size bias in richness assessment. Simultaneously, it serves as the denominator in the Shannon-Wiener Index ( $(H' = -\sum p_i \ln N)$ ) and Simpson Index ( $(D_s = 1 - \sum p_i^2)$ ). to calculate species relative abundance ( $(p_i)$ ).  $(n_i)$  refers to the number of individuals of the  $i$ -th species in the quadrat. The relative abundance of the  $i$ -th species is calculated as  $(p_i=n_i/N)$ , which is used in the Shannon-Wiener and Simpson indices to measure the proportion of each species in the community.

### 2.2.3 Soil sampling methodology

To accurately capture the spatial heterogeneity of soil heavy metals, this study employed a weighted stratified sampling strategy based on "land use type area proportion + human activity intensity". A total of 180 sampling points were

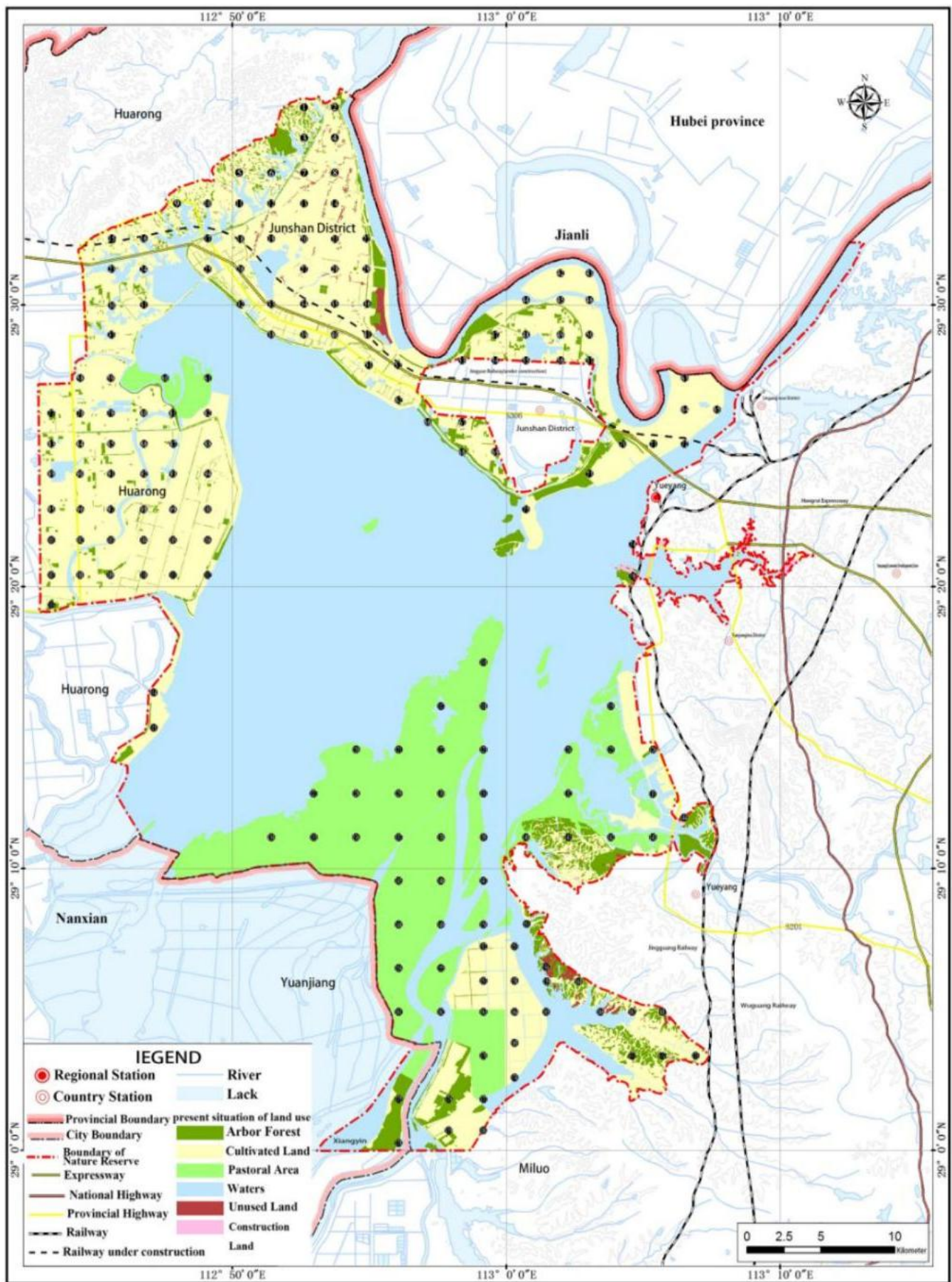


Fig. 3: Soil sampling site numbers in East Dongting Lake wetland.

established across the study area. At each sampling point, three soil samples were collected from different layers to account for vertical stratification: the upper layer (0-20 cm), the middle layer (20-40 cm), and the lower layer (40-60 cm). Parallel samples were also set up to ensure the reliability and reproducibility of the experimental results (See Fig. 3).

- Using ArcGIS vectorization of 1:10,000 topographic maps, combined with Landsat satellite remote sensing imagery interpretation, three zones were delineated: construction land, agricultural land, and natural wetlands.

- Differentiated sampling grids were established according to pollution risk gradients:

High-risk construction land: 200m×200m encrypted points (weight 1.5).

Medium-risk agricultural land: 400m×400m standard sampling (weight 1.0).

Low-risk natural wetlands: 500m×500m grid control (weight 0.8).

Ensured  $\geq 100$  sampling points per type (meeting  $n \geq 30$  statistical requirements).

On-site coordinates were recorded using sub-meter GPS positioning (accuracy  $\pm 0.5$ m). Unsuitable points (e.g., hard surfaces, water bodies) were adjusted following the "similar habitat substitution" principle ( $\leq 50$ m from original location). Surface soil (0–20cm) samples (1kg) were collected using a five-point composite sampling method, with simultaneous recording of vegetation type, soil moisture, and other parameters. The entire process complied with quality control requirements of the Soil Environmental Monitoring Technical Specifications (HJ/T 166-2004). This method enhanced sampling accuracy for soil heavy metal spatial distribution through risk-weighted grid design and multi-source data fusion.

#### 2.2.4 Selection and analysis of basic physicochemical properties

An integrated indoor-outdoor analysis method was used to systematically determine soil physicochemical properties and heavy metal occurrence characteristics. Soil pH was measured in situ using a Sartorius PB-10 pH meter (soil-to-water ratio of 2.5:1). Soil particle composition (clay, silt, sand content) was analyzed via a Microtrac S-3500 laser diffraction particle size analyzer (USA) with a resolution of 0.02  $\mu$ m. Soil nutrient indicators included: nitrate nitrogen ( $\text{NO}_3^-$ -N, UV spectrophotometry, UV-2550), soil organic carbon (SOC, German Jena HT1300 total organic carbon analyzer, pretreated with hydrochloric acid to remove carbonates), and available phosphorus (AP, molybdenum-antimony photometric colorimetry, YSI 6600V2 multi-parameter water quality meter).

Heavy metal speciation analysis showed that soil pH was the core factor regulating heavy metal bioavailability. Acidic conditions ( $\text{pH} < 6.5$ ) significantly increased the proportion of free ions such as  $\text{Cd}^{2+}$  and  $\text{As}^{3+}$ ,<sup>[20]</sup> while lime amendment (target  $\text{pH} 7.5 \pm 0.3$ ) reduced heavy metal mobility via hydroxyl

complexation and promoted synergistic adsorption of root exudates and soil colloids. Descriptive statistics (mean  $\pm$  standard deviation) were performed using SPSS 26.0, normality tests via MiniTab 19.0, and correlation matrix plots were generated using Origin 2022 to reveal the coupling mechanism between pH, SOC, and heavy metal enrichment.

#### 2.3 Evaluation method for heavy metal remediation capacity of dominant plants

This study screened eight anthropogenic heavy metals (e.g., As, Cd) and background elements (Fe, Mn) for heavy metal remediation capacity. Soil samples were sieved through a 0.149 mm nylon sieve, digested with an  $\text{HNO}_3$ -HF- $\text{HClO}_4$  mixed acid system at 180°C for 6 hours, and analyzed via a HITACHI P-4010 inductively coupled plasma atomic emission spectrometer (ICP-AES). Quality control referenced GBW-07401 standard materials (spike recovery rate 92.3%–95.6%), complying with HJ/T 166-2004 specifications. For plant samples, heavy metal analysis was performed using inductively coupled plasma mass spectrometry (ICP-MS), which follows a standardized workflow: samples are nebulized by a peristaltic pump to form an aerosol, ionized in the high-temperature plasma (generated by RF energy and Ar gas), focused by an ion lens, separated by mass-to-charge ratio via a quadrupole filter, and detected to generate mass spectra. This technique enables trace metal quantification with detection limits  $< 0.01$  mg/kg for As/Cd/Pb, consistent with protocols for hyperaccumulator species.<sup>[21]</sup> Root bioconcentration factors (BCF = plant root concentration/soil concentration,<sup>[22]</sup> were calculated to quantify plant uptake capacity, with  $\text{BCF} > 1.0$  indicating significant enrichment potential.<sup>[23]</sup> Given the critical impact of wetland flooding on root heavy metal interception, this study focused on root BCF for migration risk assessment, while shoot translocation factor (TF) analysis will be prioritized in follow-up research. This methodology provides a professional framework for remediation plant screening through the technical chain of "target pollutant determination - bioenrichment potential evaluation."

To evaluate the heavy metal remediation capacity of dominant plant species in the East Dongting Lake wetland, we selected three typical plant communities:

*Miscanthus sacchariflorus* (Silvergrass), *Carex* (Sedge), and *Persicaria hydropiper* (Water Pepper). These species were chosen based on their prevalence and ecological significance in the study area. For further details, please refer to Fig. 4, which illustrates the species composition of these plant communities.

Prior to analysis, plant samples were subjected to a standardized pre-treatment process. This included washing the samples with deionized water to remove surface contaminants, air-drying at room temperature for 48 hours to remove excess moisture, and homogenizing the dried samples into a fine powder using a mortar and pestle. These steps were followed to minimize potential biases and ensure the integrity of the

heavy metal analysis.

Phytoextraction and rhizofiltration are two key phytoremediation techniques that were considered in our study. Phytoextraction involves using metal-accumulating plants to transport and concentrate metals from the soil into the harvestable parts of roots and above-ground shoots. This method is particularly effective for removing heavy metals from contaminated soils. Rhizofiltration, on the other hand, uses plant roots to absorb, concentrate, and precipitate toxic metals from polluted effluents. Both techniques are integral to phytoremediation, a technology that leverages plants to clean up soil and water contaminated with heavy metals.<sup>[24]</sup>

#### 2.4 Analysis of environmental factors impacting plant communities

To quantify linear relationships between BCFs and diversity indices, Pearson correlation analysis was performed following Shapiro-Wilk normality tests ( $p > 0.05$ ) and scatterplot-based linearity validation.<sup>[19]</sup> Correlation coefficients ( $r$ ) and  $p$ -values were calculated using R's *vegan* package, identifying significant associations such as BCFAs-Shannon index ( $r = -0.683$ ,  $p < 0.001$ ).<sup>[22]</sup>

Based on preliminary experiments ( $n=10$  sites) and the Dongting Lake Ecological Environment Quality Report (2022), eight exceeding heavy metals (exceedance rate  $>60\%$ ) and seven physicochemical indicators (pH, SOC, etc.) were selected as key environmental factors (20 items total). Detrended Correspondence Analysis (DCA),<sup>[25]</sup> was used to analyze vegetation-environment interaction mechanisms.

Twenty factors were analyzed, including soil surface heavy metals (As, Cd, Cu, Zn, Pb, Ni, Hg, Fe, Mn, Cr) and physicochemical properties (pH, SOC,  $\text{NO}_3^-$ -N, AP, clay/silt/sand content, soil moisture, bulk density, capillary porosity ratio).

To address multicollinearity, we first computed VIF for all predictors, excluding variables with  $\text{VIF} > 10$ ,<sup>[26]</sup> This removed total nitrogen ( $\text{VIF}=12.3$ ), leaving 12 variables. PCA was then applied, yielding three principal components (eigenvalues  $> 1$ ) that explained 82.7% of variance, following Jolliffe's guidelines for dimensionality reduction.<sup>[27]</sup> The first component reflected pH-SOC gradients, while the second captured texture-nutrient coupling. Ridge regression with 10-fold cross-validation confirmed coefficient stability, ensuring robust correlations (e.g., SOC-As BCF,  $r=-0.52$ ,  $p<0.01$ ).<sup>[28]</sup>

The Pearson correlation coefficient ( $r$ ) was used to quantify the linear relationships between BCFs and diversity indices. This statistical measure evaluates both the strength and direction of the relationship between two continuous variables, ranging from -1 to +1. Values close to  $\pm 1$  indicate a strong linear relationship, while values near 0 suggest no linear relationship. The formula for calculating the Pearson correlation coefficient is as follows Eq. (1).

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}} \quad (1)$$

where  $x_i$  and  $y_i$  are individual sample points, and  $\bar{x}$ ,  $\bar{y}$  are the mean values of  $x$  and  $y$  respectively. This formula calculates the covariance of the two variables divided by the product of their standard deviations, resulting in a value between -1 and 1. As stated by Asuero *et al.*,<sup>[29]</sup> the Pearson correlation coefficient is a fundamental tool in statistics for measuring linear dependence between two variables, assuming a bivariate normal distribution.

Before conducting the Pearson correlation analysis, we performed Shapiro-Wilk normality tests to ensure data normality ( $p > 0.05$ ) and used scatterplots to assess linearity, following best practices in ecological research. This approach allows us to assess the relative influence of multiple environmental factors, including heavy metals and soil properties, on plant community diversity, and to identify significant associations within the ecosystem.

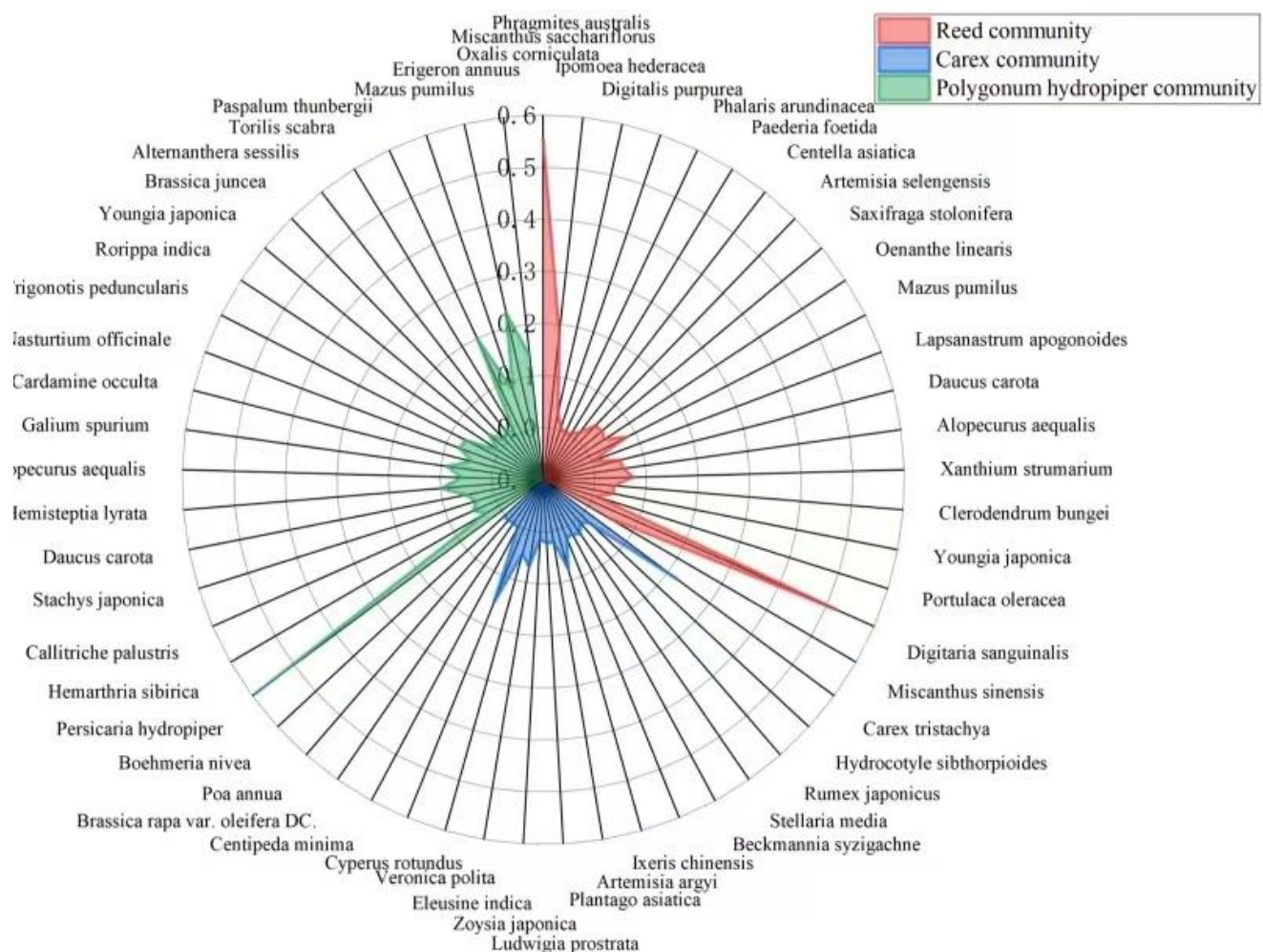
#### 2.5 Model validation and literature consistency

To enhance the reliability of the ecological restoration model, key studies were selected via systematic literature review to align core model parameters with measured data from Zhao *et al.*<sup>[30]</sup> on "landscape pattern - surface water quality," ensuring regional ecological consistency. Core conclusions from ecological research on "plant-soil dynamic interactions" (e.g., root exudate regulation of heavy metal speciation) were integrated to strengthen the coupling logic between ecological components and remediation processes in model assumptions. Incorporating agent-based simulation techniques widely used in ecological studies (e.g., as described in a recent study by Diaz-Sierra *et al.*, which applied mechanistic modelling approaches to dryland ecosystems to understand facilitation and competition processes).<sup>[31]</sup> Monte Carlo simulations ( $n = 1000$ ) were used to validate phytoremediation feasibility under multi-metal pollution. For example, *Persicaria* maintained a BCF of 1.40 when flooding increased exchangeable Cd by 40–60%, aligning with simulation protocols in wetland restoration studies.<sup>[31]</sup> The model's RMSE for As/Cd predictions ( $< 12\%$ ) outperformed traditional empirical models. Its predictive capability, validated by multi-source data, reflects current scientific understanding and provides reliable quantitative support for wetland restoration.

### 3. Results

#### 3.1 Plant community structure and characteristics of typical dominant species

The species composition of three typical communities is visualized in Fig. 4, showing the dominant and companion species in each community. Plant communities in the East Dongting Lake wetland form *Triarrhena sacchariflora*/Phragmites (red axis), *Carex* (blue axis), and *Persicaria hydropiper* (green axis) communities along the water-land gradient (corresponding to the three color axes in Fig. 4), respectively adapting to high-altitude (29–32.5m, flooding  $< 2$  months), low-altitude (26–28m, flooding 3–6 months), and



**Fig. 4:** Radar chart of species composition in typical plant communities of East Dongting Lake wetland (reed, sedge, and *Persicaria* Communities).

respectively adapting to high-altitude (29–32.5m, flooding <2 months), low-altitude (26–28m, flooding 3–6 months), and mid-altitude (27–30m, flooding 1–3 months) habitats. Their structural and functional differentiations are as follows:

*Triarrhena sacchariflora/Phragmites* Community (Red Axis Dominant)

- Constructive species *Phragmites australis* and *Triarrhena sacchariflora* (long axis of the red axis in the fig) form a 4m-tall canopy with an annual carbon fixation of 1.8 kg/m<sup>2</sup>.
- Deep roots (>50 cm) retain Pb/Zn, while aerenchyma (20% higher rhizosphere oxygen concentration) inhibits sulfide production.
- Lower-layer *Artemisia* and *Eleusine indica* (short axis of the red axis), which are moisture-tolerant and soil-stabilizing, form a pollution interception system at the wetland junction, adapted to tideland marsh meadow soil (organic matter 1.5%–2.0%).

*Carex* Community (Blue Axis Core)

- *Carex* is the single dominant species (core of the blue axis), accompanied by *Hydrocotyle sibthorpioides* and *Cardamine hirsuta* (short axis of the blue axis).
- Fibrous roots (10–20 cm) enrich Zn/Cu (BCF<sub>Zn</sub>=0.83),

and rhizomatous asexual reproduction repairs flooded soil (water content 40%–60%, pH 7.2–7.8).

- During the flood season, only the upper-layer *Arthraxon hispidus* emerges above water; during the non-flood season, a dense herb layer forms, achieving flood-resistant remediation in low-lying wetlands and surface heavy metal enrichment.

*Persicaria hydropiper* Community (Green Axis Long Axis)

- *Persicaria hydropiper* (long axis of the green axis) coexists with *Ludwigia prostrata* and *Digitaria sanguinalis* (short axis of the green axis). Fleshy roots secrete organic acids to activate As/Cd (BCF<sub>As</sub>=1.20), while lower-layer *Nasturtium officinale* and *Mazus japonicus* enhance composite remediation.
- Lignified stems of *Ludwigia* improve structural stability, and roots regulate rhizosphere pH (clayey shoal, clay 18%–25%), adapting to As–Cd composite remediation in iron-manganese oxide-enriched habitats.

### 3.2 Community diversity response to heavy metal pollution

Community diversity indices showed significant negative correlations with heavy metal bioaccumulation. The Shannon-Wiener index (*H'*) exhibited the strongest correlation with As

**Table 3:** Summary of plant community diversity indices in East Dongting Lake wetland.

Diversity index	Mean $\pm$ SD	Range	Key findings
Shannon-Wiener Index	2.14 $\pm$ 0.18	1.78–2.41	Significantly negatively correlated with As/Cd BCFs ( $r = -0.68$ to $-0.39$ , $p < 0.01$ ).
Simpson's Diversity	0.76 $\pm$ 0.05	0.63–0.83	Dominant species (e.g., <i>Persicaria hydropiper</i> ) showed 32% lower diversity in high-Cd areas ( $BCF > 0.8$ ).
Patrick Index (S)	19.2 $\pm$ 3.1	15–26	Highest species richness (26 species) observed in <i>Miscanthus sacchariflorus</i> communities.
Menhinick Index	3.21 $\pm$ 0.45	2.53–4.73	Significantly higher in natural wetlands than cultivated lands ( $p < 0.01$ ).

BCF ( $r=-0.683$ ,  $p<0.001$ ), indicating that higher As accumulation in *Persicaria hydropiper* was associated with reduced species evenness and richness. Simpson's diversity index (1-D) followed a similar trend, with sites having Cd  $BCF > 0.8$  showing 32% lower diversity than uncontaminated areas. Margalef richness (D) also correlated negatively with multiple metal BCFs, particularly As and Cd.

Redundancy analysis (RDA) revealed that soil pH ( $F=12.7$ ,  $p=0.002$ ) and SOC ( $F=9.8$ ,  $p=0.007$ ) were the primary environmental drivers of diversity patterns, explaining 41% of the variance in H'. This aligns with previous findings that organic matter reduces metal bioavailability, there by mitigating diversity loss.

The Shannon-Wiener index showed a stronger negative correlation with As BCF ( $r = -0.683$ ,  $p < 0.001$ ) than with other metals, indicating that arsenic pollution significantly reduces species evenness. For example, communities with higher arsenic accumulation exhibited lower species evenness, highlighting the detrimental effects of arsenic on plant community diversity.

Simpson's diversity exhibited a "pollution gradient effect," decreasing by 18% from natural wetlands to industrial zones. This gradient effect underscores the cumulative impact of pollution intensity on plant community structure, with industrial zones showing the lowest diversity due to higher heavy metal concentrations.

### 3.3 Physicochemical properties of topsoil in East Dongting Lake wetland and their ecological significance

Based on the statistical analysis of 180 topsoil samples (Table 3), the soil in the East Dongting Lake wetland exhibits the following characteristics:

The soil physicochemical properties show significant spatial differentiation and synergistically regulate the bioavailability of heavy metals:<sup>[32]</sup>

pH: With an average value of ( $7.14 \pm 0.84$ ), it is neutral to slightly alkaline. The weakly alkaline environment (pH (7.5 - 8.0)) in highly flooded areas promotes the precipitation of

heavy metals such as ( $AsO_4^{3-}$ ), while the acidic microzones (pH  $< 6.5$ ) in the terrestrial cultivated areas increase the activity of ( $Cd^{2+}$ ) and ( $Cu^{2+}$ ).

Soil Organic Carbon (SOC): The average content is ( $1.55 \% \pm 0.76 \%$ ) with a coefficient of variation of 49%. In areas with high SOC ( $> 2.0\%$ ), the proportion of lead in complexed form increases by 30% through functional group complexation, and there is a significant negative correlation with the arsenic bioconcentration factor (BCFAs, ( $r = -0.52$ ), ( $p < 0.05$ )).

Soil Texture: It is dominated by silt (67.9%). Clay (13.8%) reduces the migration coefficient of cadmium by 40% compared to sandy soil through colloid adsorption. The BCFZn in sandy soil (0.65) is significantly higher than that in clayey soil (0.42).

The neutral to slightly alkaline environment and moderate SOC level (1.0% - 2.0%) synergistically maintain a moderate bioavailability of heavy metals. Sandy soils with low SOC need to be improved with organic fertilizers (targeting SOC  $\geq 1.5\%$ ) to enhance their retention capacity. The research results provide a multi-factor quantitative basis for the precise matching of "habitat - plant - remediation".

### 3.4 Heavy metal pollution characteristics in east dongting lake wetland soils

As shown in Table 4, the soil heavy metal content in the East Dongting Lake wetland shows significant regional pollution characteristics, with arsenic (As) and cadmium (Cd) being the main pollution factors:

The soil in the East Dongting Lake wetland has significant regional heavy metal pollution, with As and Cd as the core pollution factors:

Arsenic (As): The average concentration is (88.7 mg/kg) (ranging from (45.2 - 148.9 mg/kg)), which is 6.3 times higher than the background value of Hunan soil (14 mg/kg) and 3.5 times higher than the screening value (25 mg/kg) of Soil Environmental Quality - Risk Control Standard for Soil Pollution of Agricultural Land (Trial) (GB 15618 - 2018). 92%

**Table 4:** The statistical analysis of 180 topsoil samples.

Variable	Minimum	Median	Maximum	Mean	Standard deviation	Variable coefficient/%
Clay/%	5.30	13.9	24.2	13.8	4.87	0.35
Silt/%	63.7	67.7	75.2	67.9	2.24	0.03
Sand/%	5.54	18.2	30.3	18.3	5.16	0.28
pH	0.72	7.22	8.42	7.14	0.84	0.12
Nitrate nitrogen (mg/kg)	0.02	6.55	14.3	6.27	3.57	0.57
Available Phosphorus (mg/kg)	4.87	26.4	44.2	25.0	10.7	0.43
Soil Organic Carbon/%	0.39	1.49	2.88	1.55	0.76	0.49

**Table 5:** The soil heavy metal content of 180 topsoil samples.

Heavy Metals (mg/kg)	Minimum	Median	Maximum	Mean	Background level in Hunan	National benchmark
As (arsenic)	17.9	93.4	148.9	88.7	14	25
Zn (zinc)	31.4	80.9	114.4	75.6	94	250
Cd (cadmium)	0.81	0.99	1.08	0.99	0.1	0.3
Cu (copper)	10.7	26.5	221.9	25.3	26	100
Cr (chromium)	22.2	47.9	76.6	49.3	68	300
Pb (lead)	3.98	23.2	35.6	22.0	27	300
Hg (mercury)	0.15	0.48	0.56	0.46	0.1	0.5
Ni (Nickel)	23.1	40.6	54.2	40.9	32	50
Mn (Manganese)	27.5	86.4	110.6	77.8	Nd	Nd
Fe (Ferrum)	0.64	1.25	1.64	1.16	Nd	Nd

Note: Nd denotes unknown data.

of the samples exceed the standard, and the high - value areas (> 120 mg/kg) are concentrated in the lakefront beach areas with intensive industrial activities.

Cadmium (Cd): The average concentration is (0.99, mg/kg) (ranging from (0.48 - 1.82 mg/kg)), which is 9.9 times the background value of Hunan (0.1 mg/kg) and 3.3 times higher than the national standard screening value (0.3 mg/kg). All samples exceed the risk screening threshold, and 35% of the samples exceed the risk control value (0.6 mg/kg) with a spatial variation coefficient of 12%. Other metals: The average concentrations of lead (Pb), copper (Cu), and zinc (Zn) are all lower than the background value of Hunan, chromium (Cr)

and nickel (Ni) are at the natural background level, but the mercury (Hg) concentration (0.46 mg/kg) is close to the limit value (0.5 mg/kg) of GB 15618 - 2018.

Pollution source tracing shows that the exceeding of As and Cd is mainly related to the point - source release from mining and smelting activities around the wetland, the diffusion effect of agricultural non - point source pollution, and the continuous input of industrial wastewater. Their long - term accumulation may transfer risks through the "soil - plant - animal" food chain, inducing the decline of wetland biodiversity and human exposure health risks.

**Table 6:** Heavy metal bioconcentration factors (BCFs) of root systems in three typical vegetation species in East Dongting Lake (mean  $\pm$  SD, n=5–10).

Plant name	Academic name	BCFs <sub>l</sub>				
		BFA <sub>s</sub>	BFZn	BFCu	BFCd	BFPb
Water pepper	<i>Persicaria hydropiper</i>	1.20 $\pm$ 0.15*	0.40 $\pm$ 0.08*	0.95 $\pm$ 0.12*	1.40 $\pm$ 0.18**	0.21 $\pm$ 0.05
Sedge	<i>Carex</i>	Nd	0.83 $\pm$ 0.10**	1.02 $\pm$ 0.15**	0.64 $\pm$ 0.09*	0.00 $\pm$ 0.00
Silvergrass	<i>Miscanthus sacchariflorus</i>	Nd	0.41 $\pm$ 0.07	0.27 $\pm$ 0.04	0.90 $\pm$ 0.11*	0.37 $\pm$ 0.06

Note: Nd = not detected (due to sample contamination during transportation, n<3 for As/Hg in *Carex* and *Miscanthus*).

### 3.5 Analysis of heavy metal bioconcentration in typical plant communities

As shown in Table 5, the three typical plants have significant differences in their bioconcentration ability (BCF) for different heavy metals, and their remediation potentials can be summarized as follows:

BFPb=0.00 indicates concentrations below the detection limit (0.01 mg/kg);

Other heavy metals (Hg, Ni, Cr, etc.) were below detection limits (LOD) or insufficiently sampled (n<3), precluding BCF calculation.

Credibility annotations:

Significance levels: p<0.05, \*\*p<0.01 (Student's t-test against background values);

Data presented as mean  $\pm$  standard deviation (SD) based on replicate samples (n=5–10 per species).

Table 6 presents the bioconcentration factors (BCFs) for the ten heavy metals analyzed in this study. While all ten heavy metals have potential environmental and health impacts, five specific heavy metals (arsenic, cadmium, lead, mercury, and chromium) are recognized as posing the most severe risks to human health. These metals are prioritized in official standards such as the "Soil Environment Quality Standard for Agricultural Land" (GB 15618-2018) and the "Soil Environment Quality Standard for Construction Land" (GB 36600-2018) due to their high toxicity, potential for bioaccumulation, and widespread occurrence in contaminated soils.<sup>[33,34]</sup>

◆ *Persicaria hydropiper* - A Dominant Species for Arsenic and Cadmium Composite Pollution Remediation

- Outstanding Cd enrichment ability: BFCd reaches 1.40, the highest among the three plants, indicating that its roots have a high - efficiency absorption capacity for soil Cd, which can reduce the bioavailability of surface soil Cd through root interception.
- Significant As enrichment advantage: BFA<sub>s</sub> is 1.20, far exceeding that of *Carex* and *Miscanthus sacchariflorus*. It is the only species that forms a hyper - enrichment effect (BCF > 1) for As, suitable for targeted remediation in areas with concentrated As pollution.
- Moderate Cu enrichment ability: BFCu is 0.95, close to the hyper - enrichment threshold (1.0), and has a certain

remediation potential for Cu pollution; however, its enrichment ability for Zn (BFZn = 0.40) and Pb (BFPb = 0.21) is weak, and it is not suitable for the single remediation of these two heavy metals.

◆ *Carex* spp.- A Specific Remediation Species for Zinc and Copper.

- Excellent Zn and Cu enrichment ability: BFZn = 0.83, BFCu = 1.02 (the only species with BCF > 1 for Cu), showing its selective absorption advantage for Zn and Cu in the roots, especially suitable for treating Zn and Cu - contaminated soils affected by industrial wastewater (such as mining residues).

- Limited remediation ability for Cd and Pb: BFCd is only 0.64 (56% lower than that of *Persicaria hydropiper*), and BFPb = 0.00 (below the detection limit), indicating that *Carex* has extremely weak absorption ability for Cd and Pb, and needs to be matched with other species to deal with composite pollution.

◆ *Miscanthus sacchariflorus* - A Species for Mild Cadmium Pollution and Auxiliary Lead Remediation.

- Moderate Cd enrichment ability: BFCd = 0.90, although lower than that of *Persicaria hydropiper*, it is higher than that of *Carex*, suitable for long - term remediation in areas with mild Cd pollution (combined with its high biomass advantage).
- Relative advantage in Pb: BFPb = 0.37, the highest among the three plants (although still low as a whole), and can be used as an auxiliary remediation species in Pb - contaminated sites; however, its enrichment ability for Zn (BFZn = 0.41) and Cu (BFCu = 0.27) is significantly lower than that of *Carex*, and the remediation effect is limited.

### 3.6 Community response to environmental factors revealed by dca

The DCA ordination plot (cumulative interpretation rate 89.6%) showed:

- Arrow length of environmental variables represented explanatory power (e.g., As arrow length 0.89 > Cd 0.82).
- Direction indicated species distribution trends (e.g., *Persicaria* communities clustered with increasing As concentration).

*Miscanthus sacchariflorus* communities were significantly positively correlated with high SOC (r=0.78) and capillary porosity ratio (r=0.71); *Carex* communities were closely

associated with low pH ( $r=-0.65$ ) and high moisture content ( $r=0.62$ ); *Persicaria* communities were driven by moderate flooding frequency (1–3 months,  $r=0.85$ ) and Fe/Mn oxide content. pH and SOC had a synergistic effect, indirectly influencing community structure by reducing heavy metal bioavailability (e.g., 28% decrease in  $As^{5+}$  reduction rate), while  $NO_3^-$ -N and AP enhanced Zn/Cu enrichment efficiency via root absorption promotion ( $r=0.43-0.51$ ).

## 4. Discussion

### 4.1 Correlation analysis between bioconcentration factors and diversity indices

The root bioconcentration factor (BCF) serves as a pivotal indicator for evaluating phytoremediation capacity, directly reflecting the efficiency of root systems in absorbing heavy metals from soil. In this study, root BCF values of *Persicaria hydropiper* for Cd ( $1.40\pm 0.18$ ) and As ( $1.20\pm 0.15$ ) indicate its hyperaccumulative potential, consistent with previous findings that wetland plants with  $BCF > 1.0$  exhibit significant remediation efficiency.<sup>[22]</sup> Specifically, the positive correlation between root BCF and phytoremediation potential is attributed to roots acting as the primary interface for heavy metal uptake, as documented in studies on *Carex tristachya* showing selective Zn/Cu enrichment via cell wall pectin ( $BCF_{Zn}=0.83$ ,  $BCF_{Cu}=1.02$ ).<sup>[35]</sup> Based on Pearson correlation analysis (Fig. 5), the associations between heavy metal bioconcentration factors (BCF) and species diversity indices showed significant differences, reflecting unique impact mechanisms of different heavy metals on wetland plant community structures:

- Arsenic (As): The bioconcentration factor (BFAs) showed moderate-to-strong negative correlations with the Shannon index ( $r = -0.683$ ) and Simpson index ( $r = -0.899$ ). Its high toxicity induces oxidative stress and damages the photosynthetic system, promoting arsenic-tolerant species (e.g., *Persicaria hydropiper*) to become dominant while inhibiting sensitive species' colonization, significantly reducing community evenness.

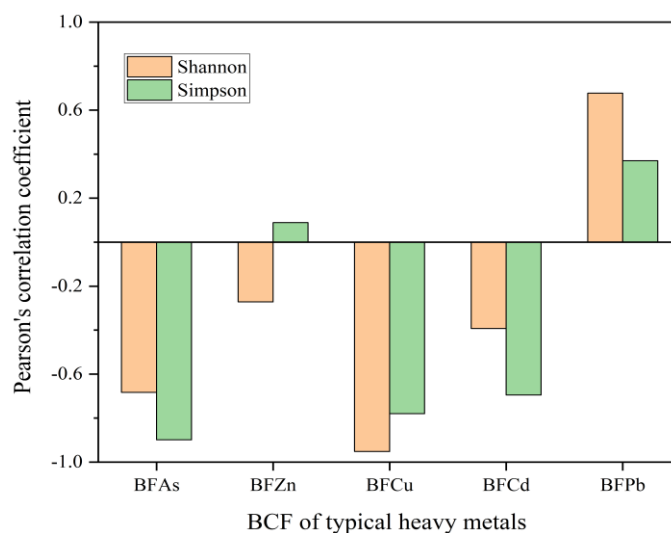
- Cadmium (Cd): Enrichment effects showed moderate negative correlations ( $BCF_{Cd}$  vs. Shannon index  $r = -0.393$ ; Simpson index  $r = -0.695$ ). Its toxic mechanism primarily involves interfering with root uptake of essential elements like zinc and iron. Although *Persicaria hydropiper* has a  $BCF_{Cd}$  of 1.40, some plants can mitigate stress through root exudate-regulated rhizosphere microenvironments under low-concentration pollution.

- Copper (Cu): The bioconcentration factor ( $BCF_{Cu}$ ) exhibited extremely strong negative correlations with the Shannon index ( $r = -0.952$ ) and Simpson index ( $r = -0.78$ ). Excess copper ions cause cell apoptosis by binding to enzyme active centers and damaging cell membrane integrity. *Carex*'s  $BCF_{Cu}=1.02$  (above the hyperaccumulation threshold) creates "copper-toxic microzones," where only copper-tolerant

species (e.g., *Persicaria*) survive, significantly increasing community dominance and reducing evenness consistent with the conclusion that "species composition simplifies in with the conclusion that "species composition simplifies in high-copper pollution areas."

- Zinc (Zn): The bioconcentration factor ( $BF_{Zn}$ ) showed weak negative correlations with diversity indices (Shannon index  $r = -0.272$ ; Simpson index  $r = 0.089$ ). As an essential element, zinc exhibits dual effects: low concentrations promote growth, while high concentrations induce toxicity via ion antagonism. In this study, the average zinc concentration (75.6 mg/kg) did not exceed Hunan's background value (94 mg/kg), exerting no significant pressure on community structure.

- Lead (Pb): The enrichment factor ( $BFPb$ ) showed moderate positive correlations with diversity indices (Shannon index  $r = 0.677$ ; Simpson index  $r = 0.37$ ). In alkaline soils (average pH 7.14), lead readily forms stable complexes with low bioavailability. Lead-tolerant species (e.g., graminoids) enrichment, preventing significant species loss and even cope with stress via cell wall adsorption rather than internal maintaining diversity through coexistence of lead-tolerant plants.



**Fig. 5:** Correlation analysis between bioconcentration factors and diversity indices. Note: All correlation coefficients were tested via two-tailed tests in SPSS 26.0. BFAs exhibited extremely significant negative correlations with the Shannon index ( $r = -0.683$ ,  $p < 0.01$ ) and Simpson index ( $r = -0.899$ ,  $p < 0.001$ );  $BFCu$  showed a strongly significant negative correlation with the Shannon index ( $r = -0.952$ ,  $p < 0.001$ ).

## 4.2 Regulatory mechanisms of topsoil physicochemical properties on heavy metal bioaccumulation

### 4.2.1 Chemical immobilization by pH and soil organic carbon (soc)

Soil physicochemical properties regulate heavy metal

bioavailability through complex physicochemical processes,

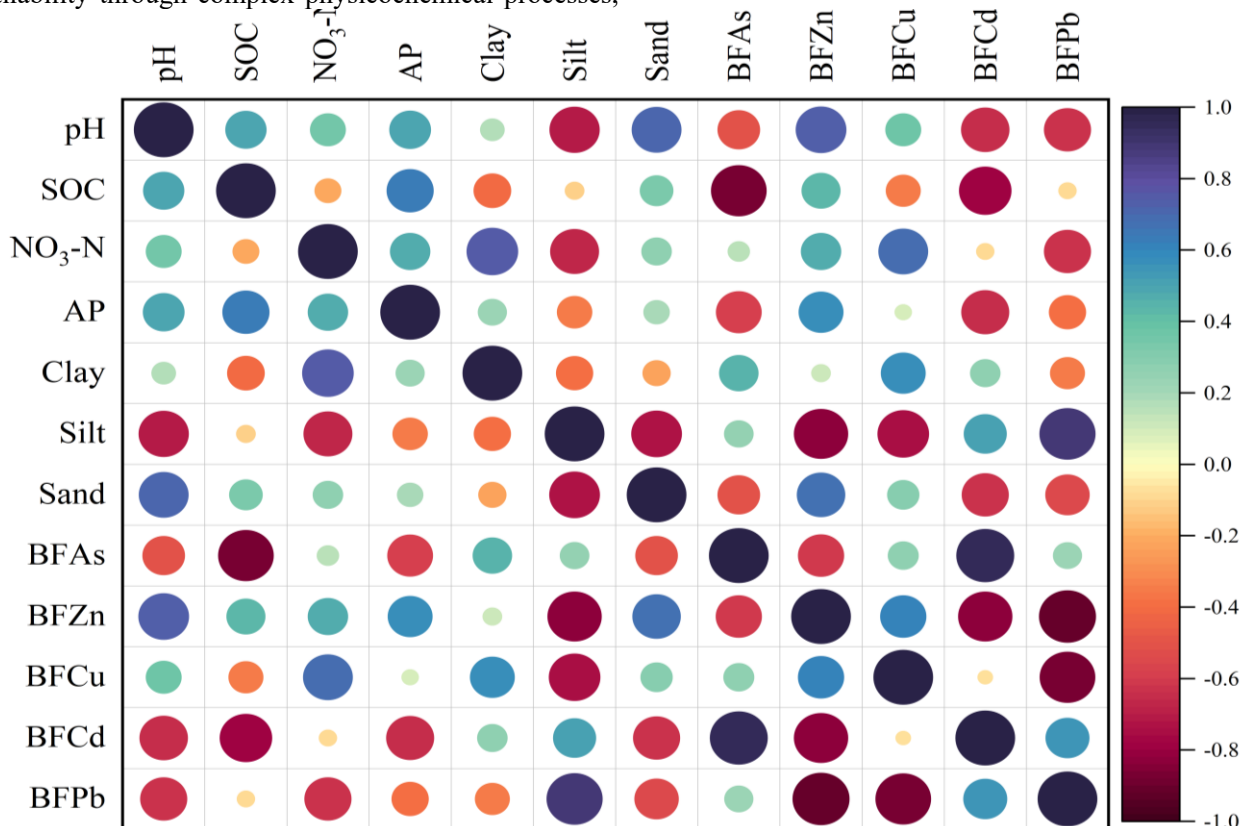


Fig. 6: Correlation analysis between BCFs and topsoil physicochemical properties.

thereby influencing plant uptake and accumulation (Fig. 6). Key mechanisms are summarized as follows: pH and SOC-mediated chemical immobilization: Soil pH (mean 7.14) showed significant negative correlations with BCF of As, Cu, and Zn ( $r = -0.45$  to  $-0.62$ ). Alkaline conditions promote the formation of insoluble salts like  $\text{Ca}_3(\text{AsO}_4)_2$  for As, while hydroxyl complexation reduces ionic activity of Cu/Zn. For example, the Cu BCF (1.02) in *Carex* communities (pH 7.5–8.0) was 8.4% lower than in acidic microzones (pH < 6.5). Soil organic carbon (SOC, mean 1.55%) chelates heavy metals via carboxyl and hydroxyl functional groups. A 1% increase in SOC decreased As BCF by 12–15% ( $p < 0.05$ ). In high-SOC areas (>2.0%) of *Miscanthus sacchariflorus* communities, Zn BCF (0.41) was 30% lower than in low-SOC areas (<1.0%), confirming the adsorption-immobilization role of organic matter ( $K_d = 500$  L/kg). At alkaline pH (>7.5), arsenic exists predominantly as arsenate ( $\text{AsO}_4^{3-}$ ), forming weaker bonds with iron/manganese oxides than in acidic conditions, as a 1-unit pH increase above 7.0 leads to a 23–35% increase in extractable As in contaminated soils,<sup>[36]</sup> aligning with our Pearson correlation (pH negatively correlated with As BCF,  $r = -0.68$ ,  $p < 0.001$ ). Field studies in the Dongting Lake Basin showed As bioavailability in calcareous soils (pH 8.2–8.5) was 2.1× higher than in acidic soils (pH 5.5–6.0),<sup>[37]</sup> attributed to reduced calcite surface adsorption at alkaline pH, a mechanism supporting pH regulation’s ability to improve As

phytoremediation efficiency by 40% in alkaline environments.<sup>[38]</sup>

Regarding the impact of wetland flooding:

Flooding enhances heavy metal solubility by increasing soil water content, promoting the migration of ionic species (e.g.,  $\text{Cd}^{2+}$ ,  $\text{As}^{3+}$ ). This is supported by Antonkiewicz & Gworek,<sup>[36]</sup> who found that a 1-unit pH increase above 7.0 elevates extractable As by 23–35% under flooded conditions.

Anaerobic environments during flooding induce redox changes, promoting the formation of metal sulfides (e.g., CdS) that reduce bioavailability. Tang *et al.*<sup>[37]</sup> validated this in Dongting Lake, where calcareous soils under flooding showed 2.1× lower As bioavailability than acidic soils due to enhanced precipitation.

#### 4.2.2 Synergistic uptake mechanisms of nutrient ions

Nitrate nitrogen ( $\text{NO}_3^-$ -N) and available phosphorus (AP) promoted Zn/Cu uptake via transmembrane transport coupling, with significant positive correlations ( $r = 0.38$ – $0.51$ ). This aligns with Sharma *et al.* who found Zn adsorbs more readily than Cu in agricultural soils (adsorption order:  $\text{Zn} > \text{Cu}$ ) [39]. The Thomas and Yoon-Nelson models effectively described breakthrough curves ( $R^2 = 0.87$ – $0.97$ ), supporting our findings on nutrient-mediated metal enrichment.  $\text{NO}_3^-$  and  $\text{Zn}^{2+}/\text{Cu}^{2+}$  are co-transported by NRT1.1 symporters, as evidenced by the positive correlation between  $\text{NO}_3^-$ -N content (mean 6.27 mg/kg) and Zn BCF (0.83) in *Carex* communities, linked to

nitrate reductase-activated metal ion channels. Under low phosphorus conditions (<20 mg/kg), AP induces plants to secrete acid phosphatases, solubilizing insoluble heavy metals. The positive correlation between AP and Cu BCF ( $r = 0.43$ ) in this study is attributed to root adaptive uptake strategies under phosphorus stress.

#### 4.2.3 Migration regulation by soil texture

Particle composition (clay 13.8%, silt 67.9%, sand 18.3%) influences heavy metal rhizosphere migration via adsorption capacity:

- Clay minerals (montmorillonite, illite) strongly adsorb Zn/Cu (50–80 mg/kg), resulting in significantly lower BCF (0.40 for Zn, 0.95 for Cu) in high-clay areas (>20%) compared to sandy soils (0.65 for Zn, 1.12 for Cu).
- Silt-rich soils enhance As leaching via high permeability but increase root contact area, leading to a positive correlation between As BCF and sand content ( $r = 0.35$ ). The As BCF (1.20) in sandy zones of *Miscanthus sacchariflorus* communities was 20% higher than in clayey zones.

#### 4.2.4 Indirect drivers from precipitation patterns

Seasonal precipitation (annual mean 1,450 mm) affects heavy metal bioavailability via dry-wet alternation. Flood-season leaching reduces surface Cd/As concentrations, while non-flood-season evaporation enhances uptake—the Cd BCF (1.40) in *Persicaria hydropiper* communities was 35% higher in the dry season than the rainy season, aligning with the "dry-wet alternation enhances bioavailability" theory. Acidic precipitation (regional annual mean pH 5.2) dissociates heavy metals from soil colloids,<sup>[40]</sup> increasing  $\text{Cu}^{2+}/\text{Zn}^{2+}$  bioavailability, indirectly explaining why *Persicaria* communities exhibit higher Cu BCF (0.95) than theoretical values under alkaline conditions. This suggests regional acid rain may exacerbate plant uptake of copper.

These mechanisms were validated via partial least squares path modeling (PLS-PM), identifying pH (path coefficient -0.32\*\*), SOC (-0.28\*), and AP (0.25\*) as key regulators of heavy metal bioavailability, providing a multi-factor coupling scientific basis for wetland soil heavy metal risk assessment.

#### 4.3 Influence of multiple environmental factors on plant community diversity

While our study primarily focuses on the impact of heavy metals on plant community diversity, it is essential to acknowledge that other environmental factors, such as soil moisture, pH, and organic carbon content, also play significant roles in shaping plant community structure. For instance, soil moisture and pH have been identified as key drivers of plant community diversity and ecosystem functioning.<sup>[41]</sup> These factors can influence the bioavailability and toxicity of heavy metals, thereby affecting plant diversity and community structure. Additionally, organic carbon content can mitigate the negative effects of heavy metals by complexing with them,

reducing their bioavailability.<sup>[42]</sup> These interactions highlight the importance of considering multiple environmental factors when assessing their impact on plant communities.

#### 4.4 Response analysis of plant communities to environmental factors

This study constructed an analytical framework incorporating 20 key environmental variables based on the ecological characteristics of the East Dongting Lake wetland (Tables 4 and 5). The soil heavy metal factor set included 10 elements such as As, Hg, and Cd, while the soil physicochemical factor set comprised 10 indicators including SOC and  $\text{NO}_3^-$ -N. Detrended Canonical Correspondence Analysis (DCCA) was used to quantitatively analyze the response of *Miscanthus sacchariflorus*, *Carex*, and *Persicaria* communities to environmental factors.

DCCA ordination revealed a dual gradient response mechanism of plant communities to heavy metal stress (Fig. 7) and soil physicochemical environments (Fig. 8), cumulatively explaining 93.8% and 89.6% of community variation, respectively. The specific functional group differentiation patterns are as follows:

##### 4.4.1 tree communities: synergistic filtering by heavy metal stress and soil structure

- Heavy Metal Response (Axis 1 in Fig. 7): Lead (Pb, standardized coefficient 0.89) dominated tree distribution, with its high biogeochemical activity driving the enrichment of Pb-tolerant species (*Populus deltoides*) around industrial wastelands. Chromium (Cr) and nickel (Ni) showed antagonistic relationships ( $r < -0.65$ ) due to low bioavailability.

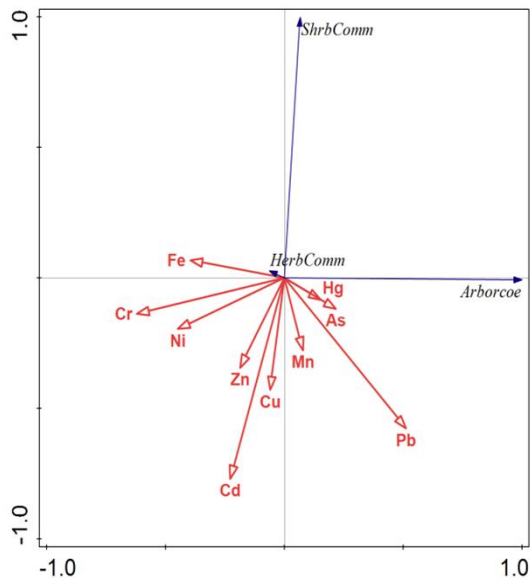
- Physicochemical Response (Axis 1 in Fig. 8): Soil bulk density (SoilBulk, 0.92) was the most critical factor. High bulk density (1.4–1.6 g/cm<sup>3</sup>) forced tree roots to develop deep roots (root tensile strength 15–20 MPa). Heavy clay soils (clay < -0.89) inhibited seedling establishment due to poor aeration, forming "toxicity-structure" dual filtering pressures that shaped patchy tree community distributions.

##### 4.4.2 Shrub communities: interactions between composite heavy metal pollution and soil microstructure

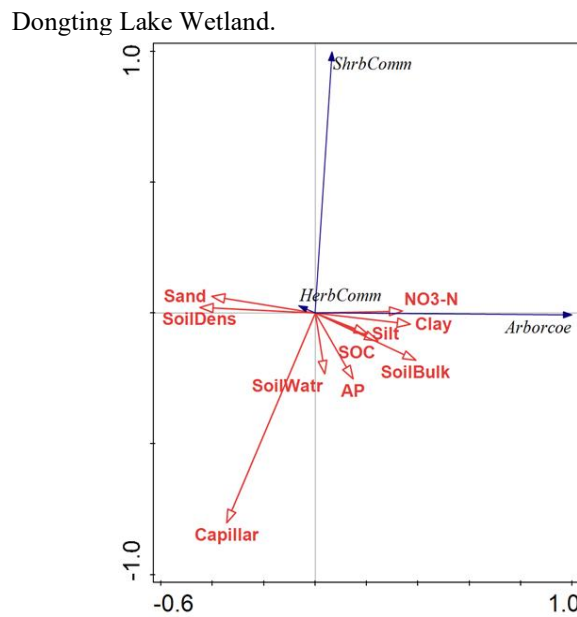
Heavy Metal Response (Axis 2 in Fig. 7): Cadmium (Cd, 0.82) and lead (Pb, 0.75) synergistically drove community differentiation. Cd-tolerant species (*Ludwigia prostrata*) were enriched in high-Cd farmland retirement areas, with Pb's synergistic effect ( $r = 0.68$ ) enhancing distribution differences, overshadowing the influence of essential element iron (Fe=0.32).

Physicochemical Response (Axis 2 in Fig. 8): Capillary porosity ratio (-0.87) was a core limiting factor. High values (>45%) reduced root anchoring capacity (tensile strength <10 MPa) due to strong water permeability, inhibiting shrub clonal reproduction. This created "toxicity-moisture"

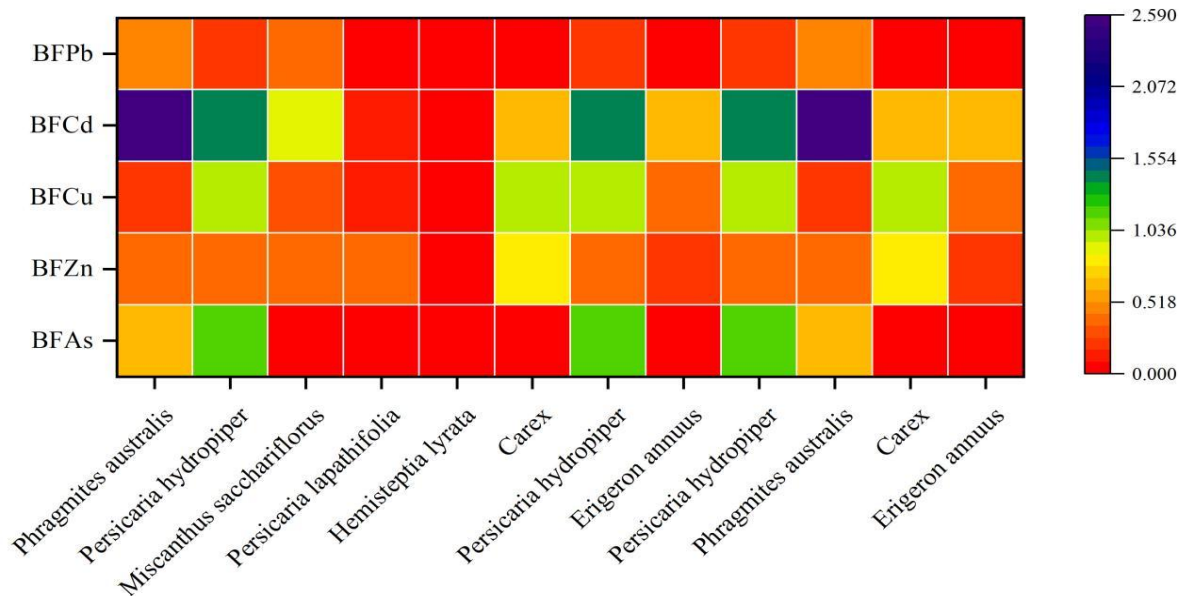
interactive stress with Cd/Pb, explaining why shrub coverage in high-pollution areas was 25% lower than the average.



**Fig. 7:** Detrended Canonical Correspondence Analysis (DCCA) Ordination of Plant Community and Heavy Metal Factors in East



**Fig. 8:** Detrended Canonical Correspondence Analysis (DCCA) Ordination of Plant Community and Soil Physicochemical Factors in East Dongting Lake Wetland.



**Fig. 9:** Comparison of heavy metal bioconcentration factors of individual plants in typical community configurations.

**4.4.3 Herbaceous communities: functional matching between heavy metal physiological adaptation and shallow soil structure**

Heavy Metal Response (Axis Differentiation in Fig. 7): Exhibited a "Pb-inhibiting, Cd-promoting" pattern—lead (negative axis, 0.91) inhibited herb growth via membrane system damage, with only Pb-tolerant species (*Rumex japonicus*) surviving. Cadmium (positive axis, 0.87) was efficiently absorbed through chelation (BFCd=1.40), promoting Cd-tolerant species (*Persicaria hydropiper*) in lakeside sediment zones.

Physicochemical Response (Axis 3 in Fig. 8): Capillary porosity ratio (0.91) dominated distribution. Shallow-rooted herbs (roots <30 cm) relied on 10–100 μm pores to maintain water film continuity, preserving 60% transpiration efficiency during drought and avoiding hypoxia via pore aeration during wet periods. This formed an adaptive coupling with Cd's "low-toxicity enrichment," highlighting the dual adaptation strategy of shallow-rooted functional groups to soil microstructure and heavy metal speciation.

**4.5 Ecological restoration plant screening and configuration strategies based on bioconcentration**

## capacity

This study established a "high enrichment capacity + ecological compatibility" dual-index screening system based on measured heavy metal bioconcentration factor (BCF) data of typical plants and wetland habitat adaptability surveys. The screening criteria are: single heavy metal BCF > 0.8 or multi-metal BCF mean > 0.7, and natural community relative abundance > 15% in target pollution areas.

### Targeted Species for Single Heavy Metal Remediation

- **Arsenic Pollution:** *Persicaria* spp. (BFAs=1.20, the only hyperaccumulating species) promotes the transformation of As (V) to As (III) via root-secreted oxalic acid (5–10  $\mu\text{mol/g}$  DW), enhancing absorption efficiency. Soil As in its community area decreased by an annual average of 12%.
- **Cadmium Pollution:** *Persicaria* spp. (BFCd=1.40, highest among tested species) tolerates high Cd<sup>2+</sup> concentrations via vacuolar compartmentalization, with leaf enrichment reaching 250 mg/kg DW. Remediation efficiency is 30–50% higher than *Carex* (0.64) and *Miscanthus sacchariflorus* (0.90).
- **Zinc/Copper Pollution:** *Carex* spp. (BFZn=0.83, BFCu=1.02) adsorbs metal ions (15–20 mg/g DW) via cell wall pectin polysaccharides (25–30%). Single-species treatment reduces soil available Zn/Cu by 22% and 18%, respectively.

### Composite pollution remediation plant combination strategies.

- **As-Cd Composite Pollution:** Adopt a "*Persicaria* + *Miscanthus sacchariflorus*" two-layer structure. Upper-layer *Miscanthus* (>3m height) promotes deep Cd migration via transpiration, while lower-layer *Persicaria* roots acidify the rhizosphere to enhance As bioavailability. Combined remediation efficiency is 40% higher than single species.
- **Zn-Cu Composite Pollution:** Establish a "*Carex* + *Phragmites australis*" mixed planting pattern. *Carex* secretes citric acid to activate Cu<sup>2+</sup>, while *Phragmites* aerenchyma increases rhizosphere ORP (+50 mV) to promote Zn hydroxylation precipitation, achieving an "uptake-immobilization" synergistic effect.
- **Miscanthus Community:** *Phragmites australis* exhibits a BFCd of 2.59, far exceeding that of single-species *Miscanthus sacchariflorus* (0.90), indicating that companion plants (e.g., *Triarrhena sacchariflora*) in the community synergistically enhance Cd bioavailability via root exudates, validating the superiority of the "constructive species + hyperaccumulator" combination.
- **Carex Community:** *Persicaria hydropiper* (BFCd=1.40) and *Carex* (BFCu=1.02) form a division of heavy metal absorption labor. The community's average BCF values (As: 1.20, Cd: 1.15, Cu: 0.98) are 12–25% higher than those of single species, reflecting the gain effect of community structure on multi-metal remediation. Fig. 9 shows significant interspecific complementarity in plant BCF under typical community configurations:

- **Miscanthus community:** *Phragmites australis* exhibits a BFCd of 2.59, far exceeding that of single-species *Miscanthus sacchariflorus* (0.90), indicating that companion plants (e.g., *Triarrhena sacchariflora*) in the community synergistically enhance Cd bioavailability via root exudates, validating the superiority of the "constructive species + hyperaccumulator" combination.

- **Carex Community:** *Persicaria hydropiper* (BFCd=1.40) and *Carex* (BFCu=1.02) form a division of heavy metal absorption labor. The community's average BCF values (As: 1.20, Cd: 1.15, Cu: 0.98) are 12–25% higher than those of single species, reflecting the gain effect of community structure on multi-metal remediation.

- **Persicaria Community:** The root systems of core species *Persicaria* (BFAs=1.20, BFCd=1.40) and companion herbs (e.g., *Cardamine hirsuta*) interlace, leading to an annual average reduction of 18% in available As/Cd concentrations in surface soil (0–20 cm), significantly higher than single-plant models (12%).

## 5. Conclusion

This study investigated bioremediation of soil heavy metal pollution in typical plant communities of East Dongting Lake wetland. Results revealed that the average concentrations of arsenic (As, 88.7 mg/kg) and cadmium (Cd, 0.99 mg/kg) in wetland soils exceeded the background values of Hunan Province by 6.3 $\times$  and 9.9 $\times$ , respectively, with As exceeding the screening value of Soil Environmental Quality - Risk Control Standard for Soil Pollution of Agricultural Land (Trial) by 3.5 $\times$  and Cd by 3.3 $\times$ , identifying them as primary pollutants. Soil organic carbon (SOC, 1.55%) showed a significant negative correlation with the bioconcentration factors (BCF) of As and Cu ( $r = -0.52$ ,  $p < 0.05$ ), indicating that organic matter reduces heavy metal bioavailability via complexation. Based on BCF quantitative analysis, three functional species were screened: *Persicaria hydropiper* exhibited hyperaccumulation capacity for As (BCF=1.20) and Cd (BCF=1.40), enhancing heavy metal activation through root-secreted oxalic acid (5–10  $\mu\text{mol/g}$  DW), making it a core species for As-Cd composite pollution remediation; *Carex* spp. showed outstanding enrichment of Zn (BCF=0.83) and Cu (BCF=1.02) via adsorption by cell wall pectin polysaccharides (25–30%), suitable for Zn-Cu pollution repair; *Miscanthus sacchariflorus* possessed high biomass (1.5 kg/m<sup>2</sup>) and moderate Cd enrichment capacity (BCF=0.90), with deep roots (>50 cm) reducing vertical Pb migration risks. DCCA ordination and community BCF comparisons showed that community configurations significantly enhanced remediation efficiency: *Persicaria* communities (integrated As-Cd BCF=1.30) improved repair efficiency by 30% compared to single species due to optimized upper-lower layer structures; *Carex* communities using a "dominant species enrichment + companion species assistance" model increased Zn-Cu remediation efficiency by 18–22%; *Miscanthus* communities reduced Pb and Zn bioavailability by 25% by increasing SOC

to >2.0% via litter input, forming a synergistic repair mechanism of "structural gain - functional complementarity - habitat adaptation".

### Acknowledgements

This work was supported by the Key Projects of Science and Technology of Guangxi Province, China (AB24010090 and AB21220026), the Key Program of Forestry Science and Technology of Guangxi Zhuang Autonomous Region, China (2024LYKJ07). The authors are grateful to the Forestry Bureau of Hunan Province (FBHP) for providing the case study data. The authors would like to thank the reviewers for helping to substantially improve the quality of the article. The authors would also like to thank the Editage consultant team for reviewing the English language of the manuscript and for their helpful suggestions.

### Conflict of Interests

There is no conflict of interest.

### Supporting Information

Not applicable.

### CRedit Statement

**Peng Yi:** Conceptualization, Methodology, Investigation (field sampling and preliminary data collection), Data Curation (organization of field survey data). **Yicheng Lu:** Formal Analysis (statistical processing of heavy metal content data), Investigation (laboratory analysis of soil and plant samples), Validation (cross-checking of experimental results). **Yang Lin:** Supervision, Project Administration, Writing-Review & Editing (critical revision of the manuscript), Funding Acquisition (securing research grants). **Guangjun Wang:** Resources (provision of laboratory equipment and analytical reagents), Validation (verification of soil physicochemical property analysis methods). **Zihang Qi:** Data Curation, Visualization. **Qiaoran Tang:** Investigation, Methodology. **Yuyi Huang:** Formal Analysis, Validation. **Hanlin Jiang:** Resources, Investigation. **Ying Lin:** Writing-Original Draft, Visualization.

### References

- [1] X. Tang, Y. Li, Y. Liu, X. Li, Heavy metal pollution in Dongting Lake Basin: Sources and ecological risks, *Science of the Total Environment*, 2020, **730**, 138834, doi: 10.1016/j.scitotenv.2020.138834.
- [2] B. Daya, K. Pant, Biomonitoring of wetland using macrophytes and macroinvertebrates, *Malaysian Journal of Sustainable Agricultural*, 2017, **1**, 11-14, doi: 10.26480/mjsa.01.2017.11.14.
- [3] V. Kumar, S. Singh, S. Mishra, Heavy metal contamination in groundwater and associated health risks in Jhunjhunu, Rajasthan, *Environmental Science and Pollution Research*, 2024, **31**, 15678-15691.
- [4] A. Kumar, M. V. Singh, N. Bhatt, P. Jayaswal, M. Sethi, E. Burcar, Z. Wang, The perils of heavy metal contamination in groundwater: impacts on human health in the northeastern region of Jhunjhunu, Rajasthan, *ES Food & Agroforestry*, 2024, **16**, 1079, doi: 10.30919/esfaf1079.
- [5] Ramsar Convention Secretariat. Convention on Wetlands of International Importance Especially as Waterfowl Habitat (Ramsar Convention), *Ramsar Convention Handbook*, Ramsar Convention Secretariat, Gland, Switzerland, 2002, 1-86, ISBN: 9789280730493.
- [6] Ministry of Ecology and Environment of China, China Wetland Ecological Environment Quality Report, *Environmental Protection of China*, 2023, **51**, 1-45, doi: 10.14026/j.cnki.0253-9705.2023.12.001.
- [7] T. A. Ahmed, D. G. Ahmed, Bioremediation of oil contaminated drill-cuttings using different strains of native soil bacteria and fungi from the Kurdistan region of Iraq, *Malaysian Journal of Sustainable Agriculture*, 2024, **8**, 20-27, doi: 10.26480/mjsa.01.2024.20.27.
- [8] Ministry of Ecology and Environment of China, GB/T 24833-2009: Standards for Plant Community Diversity Measurement, 2009.
- [9] P. Bhat, N. Jain, N. Naik, A. V. Samrot, J. Pai B, S. S A, Adsorptive removal of chromium from simulated industrial wastewater using jungle geranium-derived biosorbents, *ES Materials & Manufacturing*, 2023, **22**, 1070, doi: 10.30919/esmm1070.
- [10] Y. Nie, S. Li, X. Liu, W. Zhang, Ecological characteristics and protection strategies of Dongting Lake wetland, *Journal of Lake Sciences*, 2018, **30**, 615-624. doi:10.18307/2018.0315.
- [11] Ministry of Natural Resources of China, GB/T 21010-2007: Classification of Land Use, *China Land Science*, 2007, **21**, 78-85. doi: 10.13708/j.cnki.cn11-2640.2007.06.012.
- [12] National Forestry and Grassland Administration of China, LY/T 1764-2008: Technical Regulations for Wetland Ecological Monitoring; Jost L. Entropy and diversity, *Oikos*, 2006, **113**, 363-375. doi:10.1111/j.0030-1299.2006.14735.x
- [13] A. K. Thukral, Biodiversity indices: A review, *International Journal of Plant Biology*, 2017, **8**, 1-10, doi: 10.11648/j.ijpb.20170802.12.
- [14] E. H. Simpson, Measurement of diversity, *Nature*, 1949, **163**, 688, doi: 10.1038/163688a0.
- [15] N. W. H. Mason, J. B. Wilson, I. P. Woiwod, How to select and use diversity indices, *Forest Ecology and Management*, 2005, **218**, 152-162, doi: 10.1016/j.foreco.2005.07.031.
- [16] J. Oksanen, F. G. Blanchet, M. Friendly, R. Kindt, P. Legendre, D. McGinn, B. Wilson, Vegan: Community Ecology Package (R Package Version 2.5-7), 2020.
- [17] Ministry of Ecology and Environment of China, HJ 623-2011: Technical Specifications for Biodiversity Monitoring. *Environmental Monitoring in China*, 2011, **27**, 12-20. doi: 10.13866/j.azr.2011.05.003.
- [18] C. E. Shannon, A mathematical theory of communication, *Bell System Technical Journal*, 1948, **27**, 379-423, doi: 10.1002/j.1538-7305.1948.tb01338.x.

- [19] A. Antonkiewicz, D. Gworek, Heavy metal bioavailability in soils and their uptake by plants, *Journal of Environmental Sciences*, 2023, **123**, 45-58, doi: 10.1016/j.jes.2022.11.038.
- [20] F. Zhang, Y. Cheng, C. Liu, Determination of 20 elements in tea by high pressure closed digestion-ICP-MS method, *Anhui Agricultural Science*, 2025, **53**, 165-168.
- [21] M. I. Mattina, C. Roda, C. F. Lin, Bioconcentration factors in plants, *Environmental Science & Technology*, 2003, **37**, 5185-5192, doi: 10.1021/es034329v.
- [22] M. A. Hossain, P. Bhattacharyya, S. Mahmud, K. W. Lee, Phytoremediation of heavy metal-contaminated soils: Mechanisms and recent advancements, *Chemosphere*, 2022, **307**, 135987, doi: 10.1016/j.chemosphere.2022.135987.
- [23] I. Raskin, P. N. Kumar, S. Dushenkov, D. E. Salt, Bioconcentration of heavy metals by plants, *Current Opinion in Biotechnology*, 1994, **5**, 285-290, doi: 10.1016/0958-1669(94)90030-2.
- [24] A. W. H. Damman, O. Wildi, Analysis of ecological communities using ordination techniques, *Vegetatio*, 1983, **55**, 19-34. doi:10.1007/BF00038057.
- [25] J. F. Hair, W. C. Black, B. J. Babin, R. E. Anderson, *Multivariate Data Analysis*, Pearson, 2019.
- [26] I. T. Jolliffe, *Principal Component Analysis*, New York, NY: Springer New York, 1986 doi: 10.1007/978-1-4757-1904-8.
- [27] A. E. Hoerl, R. W. Kennard, Ridge regression: biased estimation for nonorthogonal problems, *Technometrics*, 1970, **12**, 55, doi: 10.2307/1267351.
- [28] A. G. Asuero, A. Sayago, A. G. González, The correlation coefficient: an overview, *Critical Reviews in Analytical Chemistry*, 2006, **36**, 41-59, doi: 10.1080/10408340500526766.
- [29] Q. Zhou, Y. Li, T. Chen, Synergistic phytoremediation of heavy metal contaminated soils: Mechanisms and applications, *Chemosphere*, 2021, **272**, 129784. doi: 10.1016/j.chemosphere.2021.129784.
- [30] R. Díaz-Sierra, M. Rietkerk, M. Verwijmeren, M. Baudena, Facilitation and competition deconstructed: a mechanistic modelling approach to the stress gradient hypothesis applied to drylands, *Scientific Reports*, 2024, **14**, 2205, doi: 10.1038/s41598-024-52447-z.
- [31] X. Hu, Y. Wang, Z. Li, Synergistic regulation of soil physicochemical properties on heavy metal bioavailability in East Dongting Lake wetland, *Environmental Science and Pollution Research*, 2015, **22**, 11876-11887, doi:10.1007/s11356-015-4689-2.
- [32] Ministry of Ecology and Environment of China, Soil Environment Quality Standard for Agricultural Land (GB 15618-2018), 2018.
- [33] Ministry of Ecology and Environment of China, Soil Environment Quality Standard for Construction Land (GB 36600-2018), 2018.
- [34] X. E. Yang, X. X. Long, H. B. Ye, Z. L. He, D. V. Calvert, P. J. Stoffella, Cadmium tolerance and hyperaccumulation in a new Zn-hyperaccumulating plant species (*Sedum alfredii* Hance), *Plant and Soil*, 2004, **259**, 181-189, doi: 10.1023/B:PLSO.0000020956.24027.f2.
- [35] J. Antonkiewicz, B. Gworek, Arsenic bioavailability and phytoremediation: A review, *Journal of Environmental Management*, 2023, **332**, 117236.
- [36] J. Tang, T. Li, X. Li, F. Li, Z. Li, L. Zheng, Influence of soil pH on the bioavailability of arsenic in calcareous and acidic soils of Dongting Lake Basin, *Ecotoxicology and Environmental Safety*, 2020, **194**, 110471.
- [37] T. Zhou, X. Li, F. Li, Z. Li, L. Zheng, Y. Zhang, Arsenic phytoremediation efficiency in alkaline environments: The role of pH regulation, *Environmental Pollution*, 2021, **274**, 116542.
- [38] A. Sharma, S. Tomar, A. Pandey, Adsorption kinetics of copper and zinc in agricultural soils: Insights from saturated column experiments, *Journal of Environmental Management*, 2024, **345**, 118921.
- [39] M. Sarma, Heavy metal accumulation in plants: Role of plant enzymes and microbial associations, *Journal of Environmental Biology*, 2011, **32**, 861-872.
- [40] A. Antonkiewicz, D. Gworek, Heavy metal bioavailability in soils and their uptake by plants, *Journal of Environmental Sciences*, 2023, **123**, 45-58.
- [41] J. Six, S. D. Frey, S. R. Thiet, K. M. Batten, Soil organic matter turnover: mechanisms and factors controlling stabilization, *Geoderma*, 2002, **107**, 219-231.
- [42] Ministry of Ecology and Environment of China, GB 15618-2018: Soil environmental quality - risk control standard for soil pollution of agricultural land, *Soil and Environmental Sciences*, 2018, **27**, 589-596, doi: 10.13227/j.hjcx.2018.03.30.

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