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Heavy metal accumulation and health risk assessment in *S. alterniflora Loisel.* and native plant *Suaeda salsa (L.) Pall.* in Dongtai Tiaozini wetland

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Coastal wetlands play an irreplaceable role in the global ecosystem, and both human activities and natural factors may lead to the contamination of Tiaozini coastal wetland with heavy metals. The study was conducted to determine the contents of eight heavy metals, Hg, Cd, Cr, As, Pb, Cu, Ni, and Zn, in the above-ground and below-ground parts of the plants and in the rhizosphere sediment, using the invasive species S. alterniflora and the native plant S. glauca, calculating the geoaccumulation index (Igeo), bioaccumulation factor, transfer factor, total target risk quotient (TTHQ), and carcinogenicity risk (CR), to analyze the transfer characteristics and potential health risks to human beings of the heavy metals in plants. This study aims to investigate the enrichment characteristics of the dominant plant, *S. alterniflora Loisel. (S. alterniflora)* and *Suaeda salsa (L.) Pall. (S. glauca)*. Regarding heavy metals, eight common heavy metal elements were selected, including Hg, Cd, Cr, As, Pb, Cu, Ni, and Zn, and examined their content in surface sediments and different parts of the two plants. The transfer characteristics of heavy metals in the plant body and their potential health risks to humans were also analyzed. These findings suggest that both plants accumulate higher concentrations of heavy metals in their below-ground parts. Cr, Cu, and Zn had the highest average concentrations in both plants. Geoaccumulation index (Igeo) indicated that the Tiaozini Wetland is not yet contaminated. *S. alterniflora* had transfer factors less than 1 for all heavy metals, while *S. glauca* had transfer factors greater than 1. Both plants had a certain purifying effect on heavy metal pollution in wetlands, including Cr, Cd, Cu, and Zn. However, Cr and As in the below-ground part of *S. alterniflora* and Cr in the above-ground part of *S. glauca* had a target hazard quotient (THQ) greater than 1, indicating a potential health risk to humans, but the carcinogenic risk is low. For other heavy metals, THQ was less than 1, indicating no health risk. The total target hazard quotient (TTHQ) of different parts of both plants was greater than 1, which must be taken into account when considering their suitability as edible resources.

KEYWORDS

Tiaozini, coastal wetland, *S. alterniflora Loisel.*, *Suaeda salsa (L.) Pall.*, heavy metals and health risks

1 Introduction

Coastal wetlands are crucial components of interlinked land and sea ecosystems and perform vital ecological roles such as carbon sequestration (Chen and Lee, 2022), pollution remediation, improvement of coastal water quality, protection of biodiversity, migratory bird habitats, mitigating oceanic disasters (Hongyi et al., 2009), and regulating the climate. They also bring significant environmental and economic benefits to coastal regions (Sun et al., 2018). However, under the multiple impacts of land, ocean, and human activities, coastal waters often become the most polluted parts of marine areas, and coastal wetlands have become sources and sinks of various pollutants such as heavy metals (Cui et al., 2016; Ahmed et al., 2018). Heavy metals exist in various environmental media, with high concealment, long persistence, difficult biodegradation, and difficult remediation characteristics (Li and Zhang, 2010; Varol, 2011). Heavy metal elements enter sediments through various physical, chemical, and biological processes, and some are released back into the ocean under the action of waves and tides, or absorbed by plants, etc., affecting marine organisms, marine ecosystems, and water quality safety (Yin et al., 2016), and further affecting human health under the enrichment of the food chain (Habib et al., 2016).

Dongtai is located in the southern part of Yancheng, Jiangsu Province. It boasts an extensive coastline of 85 km and a near-shore and coastal wetland area of 2116.7 km^2. It is estimated to be expanding into the sea at a rate of approximately 150 m per year, providing a significant natural resource for the ongoing ecological development of new land each year (Bai et al., 2022; Tian et al., 2022). The Tiaozini coastal wetland in Dongtai is the first of its kind and the second coastal wetland to be recognized as a World Natural Heritage Site [China's Yellow (Bohai) SeaBird Habitat (Phase I)]. However, both anthropogenic activities (agriculture, reclamation (Jing et al., 2012), etc.) and natural factors (migratory bird roosting activities (Berglund, 2018), phytoplankton (Lin et al., 2002), and hydrodynamic conditions (Cai et al., 2023), etc.) may lead to heavy metal pollution in Tiaozini wetland. The vegetation in Tiaozini wetland spans from the sea to the land and exhibits different ecological successions, with the dominant species being *S. alterniflora*, *S. glauca* and reeds. *S. alterniflora* is mainly found in the intertidal zone beyond the embankment. It is a perennial salt marsh plant belonging to the Poaceae family that was introduced to China for stabilizing beaches, preventing waves and wind. However, due to its strong reproductive and propagation ability, *S. alterniflora* has now become an invasive alien plant, posing several negative impacts on the local natural ecosystem (Zhao et al., 2022; Zhang et al., 2023). In recent years, various researchers have explored the resource utilization of *S. alterniflora* and identified its nutritional and medicinal properties, particularly its flavonoid compounds, which possess the potential to reduce blood glucose and lipid levels, exhibit anti-inflammatory effects, and enhance immune function (Xu et al., 2019). In addition, *S. alterniflora* possesses enrichment capabilities for heavy metals in wetland areas (Zhang et al., 2020; Zhang et al., 2022). *S. glauca* is primarily found in the breeding grounds of black-headed gulls within the embankment. It is an annual herbaceous plant that belongs to the Chenopodiaceae Suaeda genus. This plant is capable of improving the soil's ecological environment in wetlands, as it effectively reduces soil salinity. The metabolic activity and litter produced by *S. glauca* can enhance soil microorganism activity, while also having the ability to enrich certain heavy metal elements (Joshi et al., 2020; He et al., 2022).

In this study, the dominant plants in the coastal wetland of Tiaozini coastal wetland, *S. alterniflora* and *S. glauca*, were used to determine the contents of eight common heavy metals (Hg, Cd, Cr, As, Pb, Cu, Ni, and Zn) in the surface sediments and in different parts of the plant body, calculating the geoaccumulation index (Igeo), bioaccumulation factors, transfer factors, total target hazard quotient (TTHQ) and the carcinogenic risk (CR) of the different heavy metals in the two plants, to analyze the transfer characteristics and potential health risks to human beings of the heavy metals in plants.

2 Materials and methods

2.1 Study area profile

The research area is situated in Tiaozini coastal wetland, Dongtai, Jiangsu, facing the Yellow Sea. Its geographic coordinates are between 32°33′N-32°85′N and 120°07′E-120°96′E. It falls under the transitional zone between the North Subtropical and Warm Temperate Zones and exhibits characteristics of a marine monsoon climate, with an average annual precipitation of 900–1,068 mm and an average annual temperature of 13.5°C–14.6°C. The soil in the region is alkaline sediment loamy coastal saline soil. Tiaozini is situated at the intersection of a radial underwater sand ridge group and the middle part of Jiangsu coast. It is the largest nearshore tidal flat wetland found in the middle of Jiangsu coast. The formation and development of the radial sand ridge group are facilitated under the influence of the water-sand dynamic environment (Hu et al., 2022). The transportation mechanisms of tidal currents and sediment have shaped the landscape and demonstrated the developmental direction of the tidal flats. Its coverage extends from the initial embankment of Tiaozini Phase I towards the east to Dongdagang, and from the outer harbor passageway of Liangduo River entrance to the south to the outer harbor passageway of Fangtang River entrance.

2.2 Sample collection

The experiment took place in October 2022, during the time of peak plant biomass and maximum absorption and accumulation of elements in the intertidal zone and *S. glauca* area of the study site.

Plant sampling: due to the irregularity of the growth area of the *S. glauca*, six representative sampling sites (JP1-JP6) were randomly selected, and 3-4 complete *S. glauca* plants were dug out with a plastic shovel in each sample site, divided into above-ground parts (SSU) and below-ground parts (SSD), and then put into polyethylene self-sealing bags and sealed for low-temperature storage. Two more evenly distributed sampling areas with the largest biomass were selected (CP1 and CP2) in the *S. alterniflora* zone. In CP1 and CP2 two sample zones were set up evenly distributed, larger biomass of 1 m × 1 m sample squares, each sample square using the plum blossom method to collect 4-5 complete plants of *S. alterniflora*, which were divided into above-ground parts (SAU) and below-ground parts (SAD), then

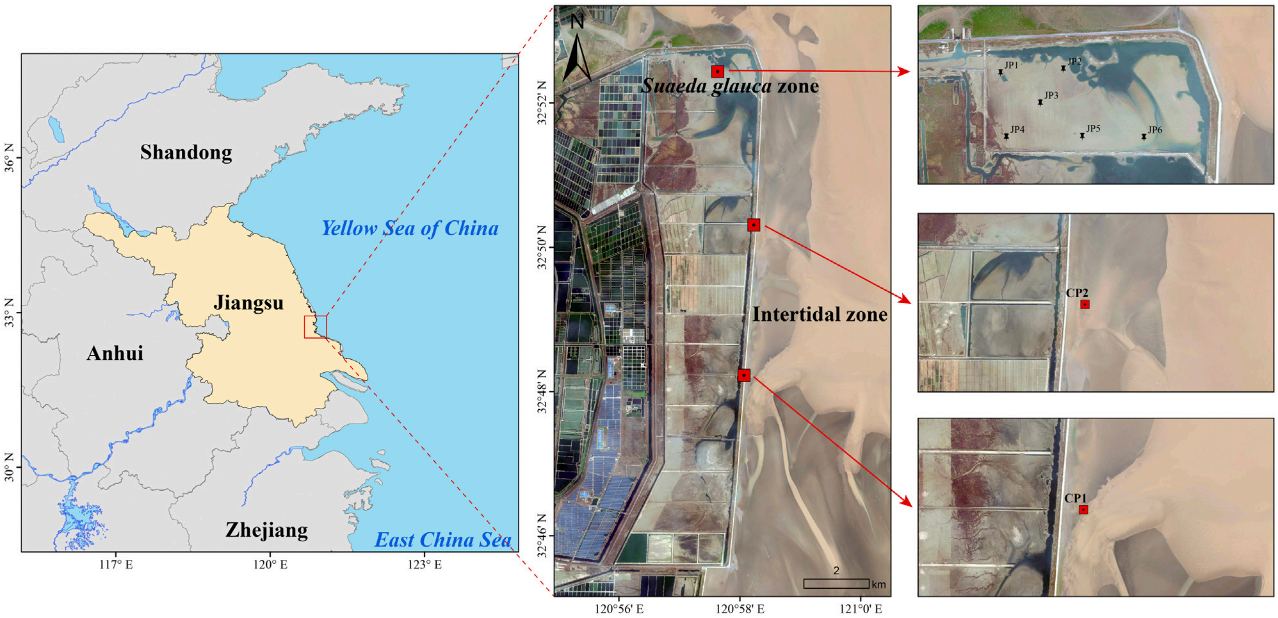

FIGURE 1
Location of the study area and distribution of sampling points.

put into polyethylene self-sealing bags and sealed and preserved at low temperatures.

Sediment sampling: in the sampling points JP1-JP6 in the *S. glauca* area, the rhizosphere sediment of *S. glauca* samples was collected by using a plastic shovel, and the sediment samples were put into polyethylene self-sealing bags, sealed and preserved at low temperatures. In the *S. alterniflora* area CP1 and CP2 two sample zones set up in the sample square to collect the rhizosphere sediment samples of *S. alterniflora* samples, into the polyethylene self-sealing bags sealing, and finally all the samples will be preserved at low temperature and transported back to the laboratory.

Figure 1 shows the specific locations of the sampling points.

2.3 Sample treatment and experimental analysis

The sediment samples were freeze-dried until a constant weight was achieved. They were then purified to remove any impurities and ground to a fine consistency before being sifted through a 100-mesh (150 μm) nylon screen and stored at 4°C for future experiments. The plant samples were washed thoroughly with tab water to remove large particles. Three rinses with deionized water were performed before the plants were air-dried. The plants were separated into above-ground and below-ground parts, each of which was placed in a drying oven at 45°C for 10 min. After cooling, the samples were ground into powder and sifted through a 40-mesh (0.425 mm) nylon screen. Finally, the samples were stored in labeled bags until needed.

0.2 g of sediment and plant samples were weighed separately and placed in digestion tubes. For sediment samples, a mixture of 6 mL nitric acid (65%–68%), 2 mL hydrofluoric acid (40%), and 2 mL hydrochloric acid (37%) was added for digestion. For plant samples, 6 mL concentrated nitric acid and 2 mL hydrogen peroxide (30%) were added and digestion was performed in a microwave according to standard procedures Take 0.2 g–0.5 g of solid rest sample and add 5 mL–10 mL, nitric acid, cover and leave it for 1 h or overnight, screw the lid of the jar tightly. The digestion is carried out in three steps, the first 120°C heating 5 min, constant temperature 5 min, followed by 150°C heating 5 min, constant temperature 10 min, and finally 180°C heating 5 min, constant temperature 20 min. After cooling, remove, slowly open the lid of the tank exhaust, with a small amount of water to rinse the inner lid, the digestion tank on a temperature-controlled hot plate or ultrasonic water bath, heating at T00°C for 30 min or ultrasonic Degas for 2 min–5 min, and then volume to 25 mL or 50 mL with water, mix well and standby, and do blank test at the same time. After cooling, the samples were transferred to an acid washing device and 1 mL perchloric acid was added to make a total volume of 10 mL with pure water. The processed samples were used to determine the concentrations of Cd, Cr, Pb, Cu, Ni, and Zn. For determination of Hg and As concentrations, 0.2 g of sediment and plant samples were respectively added with 2 mL nitric acid and 6 mL hydrochloric acid for digestion. Inductively coupled plasma atomic emission spectroscopy (ICP-OES: Thermo Fisher ICAP PRO) was used to determine the concentrations of Cd, Cr, As, Pb, Cu, Ni, and Zn, following the China National Standards (HJ781-2016). The operating conditions and measurement parameters of ICP-OES are as follows: after power on, start to evacuate the vacuum so that the vacuum degree is below 6.6e-6 Torr, and the temperature is set to 25°C. Then start to torch, and after the torch is finished, put the injection tube into about 2% nitric acid solution or ultrapure water to rinse the injection system. Edit the analytical method in advance and call the method for sample testing. Atomic fluorescence spectrophotometry was used to determine the concentration of Hg, following China National Standards (HJ680-2013). The LOD and LOQ values for studied heavy metals were displayed in Supplementary Table S1. To validate the accuracy and precision of the analysis method, each element was repeated four times, and one standard sample was analyzed. The experimental analysis error was below 20%, and the recovery rate was between 85% and 115%. Standard samples [GBW07387 (GSS-31), GBW07386 (GSS-30) and GBW07408 (GSS-08)] were provided by Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences, China (IGGE).

2.4 Geoaccumulation index (Igeo)

The geoaccumulation index, a method used by Muller to assess metal contamination in sediments (Prveena et al., 2008), not only takes into account the effects of natural factors such as geological changes, but also pays attention to anthropogenic effects, and is able to differentiate anthropogenic impacts with a high degree of accuracy. The formula is as follows (Prveena et al., 2008; Rabee et al., 2011):

$$\mathrm{Igeo} = \log_2\left(\frac{C_0}{1.5B_n}\right) \quad (1)$$

In the equation, C_0 represents the content of heavy metals in a certain part of the plant (mg/kg); 1.5 represents the background matrix correction factor due to lithogenic effects, and Bn represents the geochemical background value in the average shale of element n, where Hg, Cd, Cr, As, Pb, Cu, Ni, and Zn are 0.022, 0.089, 72, 9.5, 19.5, 21, 30.7, 67, respectively.

According to Çevik et al. (2009), the contamination level may be classified in a scale ranging from 1 to 6 ($\mathrm{Igeo} \le 0$ = unpolluted, $\mathrm{Igeo} < 1$ = unpolluted to moderately polluted, $\mathrm{Igeo} < 2$ = moderately polluted, $\mathrm{Igeo} < 3$ = moderately to strongly, $\mathrm{Igeo} < 4$ = Strongly polluted, $\mathrm{Igeo} < 5$ = strongly to very strongly polluted, $\mathrm{Igeo} > 5$ = very strongly polluted).

2.5 Heavy metal absorption and transferability

2.5.1 The bioaccumulation factor

The bioaccumulation factor (BAF) quantifies the capacity of organisms to absorb and amass heavy metals from soil ecosystems. This indicator is commonly stated as the proportion of heavy metal content in a specific organ of a plant to the corresponding element concentration in its growing soil. The BAF calculation formula is as follows (Luc et al., 2022):

$$\mathrm{BAF} = C_P / C_S \quad (2)$$

In the equation, BAF represents the biotic accumulation factor of a certain heavy metal in plants, C_P represents the concentration (mg/kg) of that heavy metal in a certain part of the plant, and C_S represents the concentration (mg/kg) of that heavy metal in the root zone sediment of that plant. $\mathrm{BAF} > 1$ indicates that the concentration of that heavy metal in a certain part of the plant is higher than in the root zone sediment, indicating that the plant has a strong ability to absorb and accumulate that heavy metal.

2.5.2 Transfer factors

The transfer factor (TF) is the ratio of the concentration of an element in the aerial parts (such as stems, leaves, flowers, and fruits) of a plant to its concentration in the below-ground parts (roots). It is commonly used to assess the transport ability of a plant for that element from roots to aerial parts. The calculation formula is as follows (Nurtjahya et al., 2023):

$$\mathrm{TF} = C_O / C_U \quad (3)$$

In the equation, TF represents the transfer coefficient of plants for a certain heavy metal, C_O represents the concentration of the heavy metal in the above–ground part of the plant (mg/kg), and C_U represents the concentration of the heavy metal in the below-ground part of the plant (mg/kg). If $\mathrm{TF} > 1$, it indicates that the plant is less sensitive to heavy metals in the soil and is more likely to transfer them to the above-ground part; but if $\mathrm{TF} < 1$, it indicates that the plant has a certain degree of resistance to heavy metals in the soil, and its ability to migrate to the above-ground part is very small.

2.6 Health risk assessment

The Target Hazard Quotient (THQ) is a method for assessing health risks associated with single and combined heavy metal exposure in plants. THQ assesses the hazard of a single heavy metal element by dividing the daily human intake by the reference dose, while TTHQ evaluates the hazard of multiple heavy metal elements by summing the THQ values for each element (EPA, 2000). The health risk assessment method for coastal plant products was used in this calculation. The formula is as follows (Kouali et al., 2022; Xing et al., 2022):

$$\mathrm{THQ} = (C_0 \times \mathrm{FIR} \times \mathrm{EF} \times \mathrm{ED}) / (R_{fDo} \times \mathrm{BW} \times \mathrm{AT} \times 1000) \quad (4)$$

$$\mathrm{TTHQ} = \sum_{i=1}^{n} \mathrm{THQ}_i \quad (5)$$

In the equation, C_0 represents the content of heavy metals in a certain part of the plant (mg/kg); FIR represents the daily consumption *per capita* (g/d); EF represents the number of days of intake per year (d/a), calculated based on 300d; ED represents exposure time (a), calculated based on 30a; BW represents body weight (kg); R_{fDo} represents the reference daily intake (mg/(kg·d)), referring to the daily tolerable intake provided by USEPA, where Hg, Cd, Cr, As, Pb, Cu, Ni, and Zn are 0.0003, 0.001, 0.003, 0.0003, 0.0015, 0.04, 0.02, and 0.3, respectively (Bortey-Sam et al., 2015); AT represents the average exposure time, calculated based on 365 d × 70 a. Referring to Zhu Yaojia et al.'s assessment of the health risk of heavy metals in different parts of *S. glauca*, the weight of an adult was set to 60 kg and the daily intake was set to 30 g. Given the limited consumption of *S. alterniflora* and *S. glauca* in local residents' diets, primarily for their health benefits, this study uses 10 g as a reference for 1/3 of the daily intake.

When the THQ and TTHQ indices are <1.0, it indicates that there is no significant health risk to the human body; when the TTHQ and THQ indices are >1.0, it indicates a greater risk to human health.

The carcinogenic risk (CR) and total carcinogenic risk (TCR) can be calculated by following formula (Liu et al., 2021):

$$\mathrm{CR} = (\mathrm{THQ} \times R_{fDo} \times \mathrm{SF}) / 1000 \quad (6)$$

$$\mathrm{TCR} = \sum \mathrm{CR}_i \quad (7)$$

In the equation, CR represents the potential carcinogenic risk through consumption of carcinogenic heavy metals; SF is the

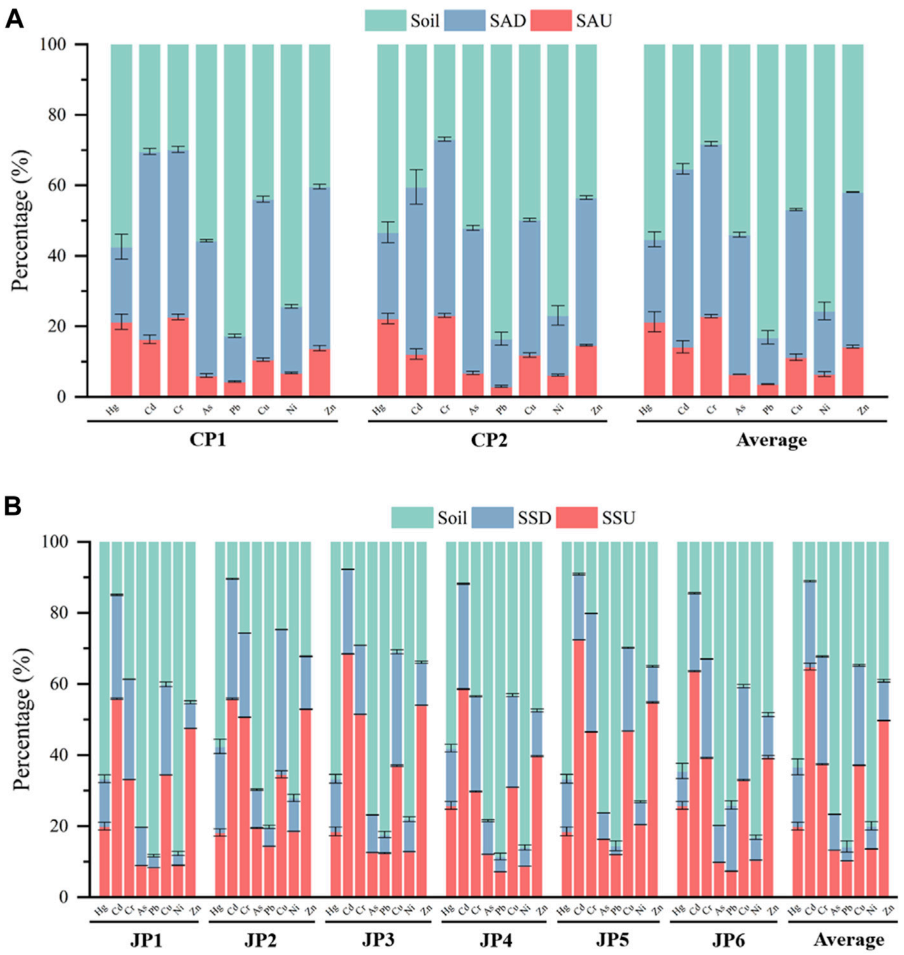

FIGURE 2
Percentage of heavy metal content in *S. Alterniflora*, *S. glauca* and their rhizosphere soil. **(A)** *S. Alterniflora*; **(B)** *S. glauca*.

slope factor of carcinogenic heavy metals (This study is considering the toxic effects of the two plants when used as edible resources, so SF is the carcinogenicity slope factor for oral ingestion); TCR is the sum of the potential carcinogenic risk of each heavy metal. The heavy metals for which SF is currently available in this study are Cd, Cr, As, Pb, and Ni, with 6.1, 0.5, 8.5×10^{-3}, and 1.7 respectively (Lin et al., 2023).

The carcinogenic risks were classified as no risk (TCR/CR < 10^{-6}), a risk that humans can tolerate ($10^{-6} \leq$ TCR/CR < 10^{-4}), and a risk that humans cannot tolerate ($10^{-4} \leq$ TCR/CR) (Rao et al., 2022; Lin et al., 2023).

2.7 Statistical analysis

Statistical software SPSS 22.0 (SPSS, Inc., Chicago, IL) and Excel 2019 were used to preprocess the data, and the single-factor analysis of variance (ANOVA) was used to measure the difference between treatments ($n \geq 3$). The difference was considered to be statistically significant at $p < 0.05$. All data were processed using Origin 2023 (Origin Lap Corp, United States).

3 Results and discussion

3.1 Plant heavy metal content and enrichment characteristics

3.1.1 Analysis of heavy metal content in plants

The levels of heavy metals present in various regions of *S. alterniflora* and the adjacent rhizosphere soil located within the intertidal zones were displayed in Figure 2A. The distribution and accumulation of distinct elements within different sections of *S. alterniflora* principally rely on the bioaccumulation of biomass and the concentration of the element present in various components (Feng et al., 2018). The concentrations of Hg, Pb, and Ni in *S. alterniflora* in the study area were significantly lower than those found in the rhizosphere soil. The order of heavy metal content was: soil > SAD > SAU, indicating that *S. alterniflora* had a minimal accumulation of Hg, Pb, and Ni and negligibly affected the concentration of these elements in the rhizosphere soil. The concentration of Cd, Cr, and Zn in *S. alterniflora* was mainly exhibited as SAD > soil > SAU, suggesting that *S. alterniflora* has a strong ability to absorb Cd, Cr, and Zn in the below-ground part.

TABLE 1 Igeo of heavy metals at sampling sites

Plant species	Sampling sites		Igeo							
			Hg	Cd	Cr	As	Pb	Cu	Ni	Zn
S. alterniflora	CP1	1	-0.24	-0.62	-1.07	-0.79	-1.17	-1.43	-1.00	-0.95
		2	-0.29	-0.43	-1.04	-0.59	-1.12	-1.29	-0.97	-0.91
		3	-0.46	-0.85	-1.08	-1.16	-1.32	-1.65	-1.09	-1.10
		4	-0.46	-0.49	-1.11	-0.66	-1.16	-1.28	-1.10	-0.94
		Average	-0.36	-0.59	-1.08	-0.79	-1.19	-1.41	-1.04	-0.98
	CP2	1	-0.46	-0.28	-0.98	-1.00	-0.96	-1.19	-0.85	-0.80
		2	-0.52	-0.28	-1.03	-1.09	-1.20	-1.42	-0.99	-0.94
		3	-0.65	-0.23	-0.85	-0.98	-0.98	-1.11	-0.76	-0.77
		4	-0.54	-0.26	-0.95	-1.02	-1.04	-1.23	-0.86	-0.84
		Average	-0.24	-0.62	-1.07	-0.79	-1.17	-1.43	-1.00	-0.95
S. glauca	JP	JP1	-0.76	-0.36	-1.07	-0.96	-1.14	-1.35	-0.94	-0.96
		JP2	-0.78	-0.49	-1.28	-1.26	-1.34	-1.84	-1.24	-1.28
		JP3	-0.85	-0.47	-1.11	-1.01	-1.22	-1.39	-0.97	-0.99
		JP4	-0.85	-0.45	-1.14	-1.12	-1.21	-1.41	-0.97	-0.98
		JP5	-0.85	-0.41	-1.13	-1.40	-1.23	-1.61	-1.06	-1.09
		JP6	-0.75	-0.15	-1.03	-1.18	-1.01	-1.33	-0.89	-0.84
		Average	-0.81	-0.38	-1.12	-1.15	-1.19	-1.48	-1.01	-1.02

The concentration of As and Cu in *S. alterniflora* was mainly exhibited in the order: soil > SAD > SAU, and unlike Hg, Pb, and Ni, *S. alterniflora* below-ground part had a certain accumulation ability for As and Cu in the soil. The results indicated that the below-ground part of *S. alterniflora* had higher element accumulation than the above-ground part. The element accumulation of *S. alterniflora* was similar in sampling points CP1 and CP2, which may be due to the similar invasion age of *S. alterniflora* in the two areas.

Based on Figure 2B, the heavy metal concentration of Hg, As, Pb, and Ni in various parts of *S. glauca* is significantly lower than the rhizosphere soil in the study area. The order of heavy metal concentration in terms of quantity is: soil > SSU > SSD, indicating that *S. glauca* has a minimal accumulation of Hg, Pb, and Ni. Moreover, it has almost no impact on the concentration of Hg, As, Pb, and Ni in the rhizosphere soil. The heavy metal content in the above-ground parts of *S. glauca* is considerably higher compared to the corresponding elements in the below-ground parts. In the accumulation of Cd, *S. glauca* demonstrates a strong ability, with the concentration order mainly as SSU > SSD > soil. Furthermore, its above-ground parts hold a higher tendency for Cd accumulation. The order of Cr, Zn, and Cu concentration in different parts of *S. glauca* as mainly SSU > soil > SSD. This shows that *S. glauca* has a strong ability to enrich the soil with Cr, Zn, and Cu, transferring most of it to above-ground parts. This ability increases the accumulation of above-ground parts. The results also reveal that the above-ground parts' accumulation of *S. glauca* is lower than the below-ground parts. In some sampling points, the abnormal high values in above-ground parts of the plant and abnormal low values in below-ground parts are related to environmental factors, such as the interactions between heavy metals and other elements in the soil (Song and Sun, 2014). At the same time, the growth periods of *S. glauca* vary across different sampling points, and the accumulation capacity and selectivity of *S. glauca* for various heavy metals also vary at different growth stages (Song et al., 2022).

On the whole, *S. alterniflora* and *S. glauca* contain relatively high concentrations of Cr, Cu, and Zn within their bodies. These heavy metals are vital elements for their growth, development, and reproduction. Appropriate levels of Cr can enhance net photosynthesis and promote healthy plant growth, but excessive Cr can have toxic effects on plants (Taufikurahman et al., 2019). Cu can be absorbed and utilized by plants to synthesize various enzymes and participate in numerous essential metabolic reactions within the plant's body (Niyoifasha et al., 2023). The biosynthesis of several enzymes in plants necessitates the utilization of zinc, and these enzymes hold particular importance for the metabolism of carbon and nitrogen in plants (Liu et al., 2022).

3.1.2 Geoaccumulation index (Igeo)

Calculate the Igeo of heavy metals in plants according to Eq. 1. The results in Table 1 show that the Igeo of heavy metals in the plants were less than 0, indicating that the Tiaozini Wetland is clean in terms of heavy metals and is not yet contaminated. Compared with other wetlands in China, the Tiaozini Wetland is the least

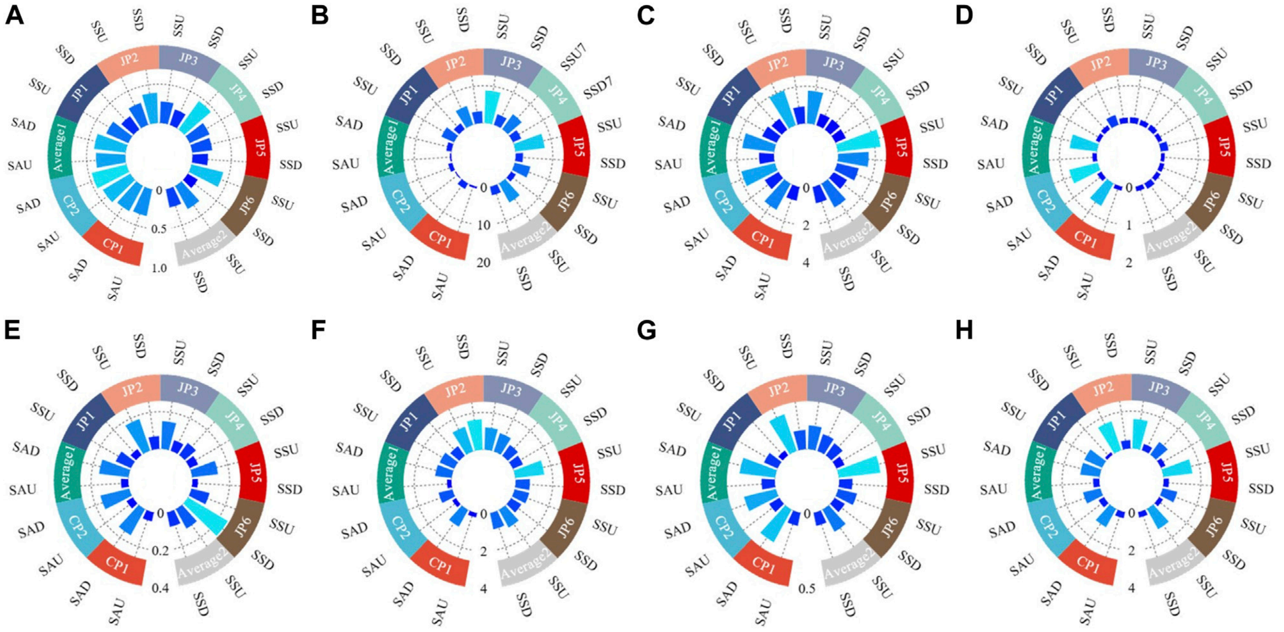

FIGURE 3
The bioaccumulation factors of each heavy metal in different parts of *S. Alterniflora* and *S. glauca*. **(A)** Hg; **(B)** Cd; **(C)** Cr; **(D)** As; **(E)** Pb; **(F)** Cu; **(G)** Ni; **(H)** Zn.

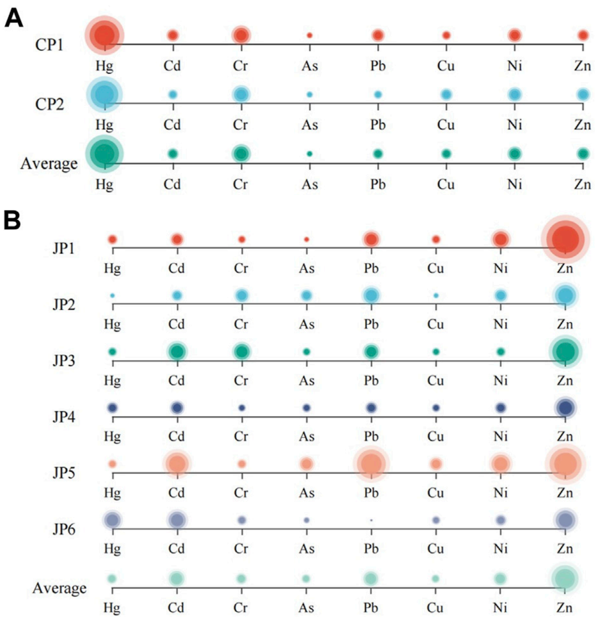

FIGURE 4
The transfer factors of S. Alterniflora and S. glauca. **(A)** *S. Alterniflora*; **(B)** *S. glauca*.

contaminated and uncontaminated, while all other wetlands are contaminated to a certain extent, and a common reason is the high concentration of Cd. The Tiaozini Wetland is not contaminated in terms of Igeo, but the Igeo of Cd is also the highest among the eight heavy metals, which is closely related to the intensity of anthropogenic activities (Wang et al., 2017; Lu et al., 2020; Hu et al., 2021). The Tiaozini wetland is China's 14th World Natural Heritage Site, the core area of China's Yellow (Bohai) Sea Migratory Bird Habitat (Phase I), and part of the area is not open to the public. In addition, the Tiaozini Wetland has been reclaimed and farmed, but the environmental protection is relatively strict.

3.1.3 Bioaccumulation factors and transfer factors of heavy metals in plants

The accumulation effect of plants on heavy metals is mainly measured by the bioaccumulation factors and transfer factor (Susarla et al., 2002).

Calculate the bioaccumulation factors of heavy metals in plants according to Eq. 2. The bioaccumulation factors (BAFs) of each heavy metal in *S. Alterniflora* and *S. glauca* were presented in Figure 3. The average BAFs of the eight heavy metal elements in above-ground parts of *S. Alterniflora* are ranked as follows: Cr (0.81) > Cd (0.42)> Hg (0.38)> Zn (0.34)> Cu (0.24)> As (0.12)> Ni (0.09) > Pb (0.04). It is observed that the above-ground parts of *S. alterniflora* have a weaker ability to accumulate heavy metals, as the average BAFs of all metals are not greater than 1. The highest accumulation ability is noted for Cr. Similarly, the average BAFs of *S. alterniflora*'s underground parts for each heavy metal are ranked as follows: Cr (1.73)> Cd (1.46)> Zn (1.05)> Cu (0.90)> As (0.74)> Hg (0.41)> Ni (0.24)> Pb (0.16), indicating a strong ability to accumulate Cr, Cd, and Zn. The order of accumulation ability of heavy metals in the underground parts is consistent with that in the above-ground parts except for Hg. The BAFs of heavy metals in the underground parts are more than twice that of the above-ground parts, suggesting that *S. alterniflora* mainly accumulates heavy metals in its underground parts. Overall, *S. alterniflora* has the potential for purifying and remediating soil contaminated with Cr, Cd, and Zn.

TABLE 2 THQ and TTHQ of heavy metals in different parts of plants

Plant species	Parts	THQ								TTHQ
		Hg	Cd	Cr	As	Pb	Cu	Ni	Zn	
S. alterniflora	SAU	0.002	0.002	0.846	0.185	0.024	0.005	0.006	0.004	1.074
	SAD	0.002	0.009	1.808	1.143	0.088	0.017	0.017	0.011	3.095
S. glauca	SSU	0.001	0.035	1.124	0.218	0.060	0.018	0.011	0.012	1.479
	SSD	0.001	0.013	0.911	0.166	0.024	0.013	0.005	0.003	1.135

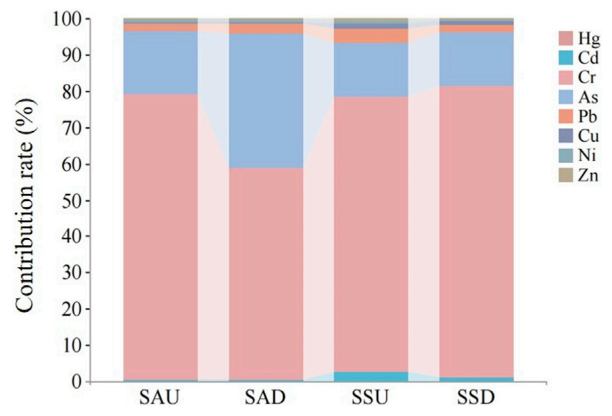

FIGURE 5
Contribution rate of each heavy metal to TTHQ of *S. alterniflora* and *S. glauca*.

Based on the average BAFs of eight heavy metal elements found in the above-ground parts of *S. glauca*, the ranking is as follows: Cd (5.85)> Cr (1.46)> Zn (1.25)> Cu (1.09)> Hg (0.34)> As (0.17)> Ni (0.16)> Pb (0.12). It is evident that Cd, Cr, Zn, and Cu have average BAFs greater than 1 in the above-ground parts of *S. glauca*, with Cd showing a particularly strong accumulation ability with a BAF of 5.85, significantly higher than that of the other heavy metals. This indicates that *S. glauca* has a remarkably strong ability to accumulate Cd in the above-ground parts. On the other hand, the BAFs of Hg, As, Ni, and Pb are all less than 1, showcasing a relatively weak accumulation ability for these heavy metals in the above-ground parts. Moving on to the BAF rankings of heavy metal elements in the underground parts of *S. glauca*, this study finds that these rankings are consistent with those in the above-ground parts. This reveals that *S. glauca* has a strong ability to accumulate Cd in the underground parts, while the accumulation ability for Cr, Zn, Cu, As, Hg, Ni, and Pb is relatively weak. The BAF rankings across the six sampling points are generally consistent with the average BAF rankings. However, there is a considerable variation in the range of BAFs for some heavy metals among the different sampling points, which may be attributed to soil pollution from heavy metals in the local study area. Compared to the eight heavy metals analyzed, *S. glauca* has a stronger accumulation ability for Cd, Cr, Zn, and Cu, which is consistent with findings from previous studies on the accumulation ability of *S. glauca* for heavy metals (Shang et al., 2020; Cui et al., 2022; Quan et al., 2022). Meanwhile, *S. glauca* exhibits a high level of Cd accumulation, while its capacity to accumulate Pb is relatively weak. The findings suggest that the accumulation capabilities of both the above-ground and underground portions for each heavy metal are essentially consistent. The bioaccumulation factors (BAFs) of heavy metals in *S. glauca*'s above-ground sections are significantly greater than those in the underground parts, with the BAFs in the former being 0–2 times that of the latter. This suggests that *S. glauca* primarily absorbs and accumulates heavy metals in its above-ground portions, which may be influenced by factors such as soil pH, moisture levels, organic matter content, and microorganisms in the growing environment and plant growth cycles. Overall, *S. glauca* has the potential to purify and remediate Cr, Cd, Cu, and Zn in the soil to some extent.

Calculate the transfer factors of heavy metals in plants according to Eq. 3. The transfer factors (TFs) of various heavy metals in the soil for *S. Alterniflora* and *S. glauca* were shown in Figure 4. The average values, from high to low, are as follows: Hg (0.92)> Cr (0.47)> Ni (0.36)> Zn (0.33)> Cd (0.28)> Pb (0.27)> Cu (0.26)> As (0.16) (Figure 4A). All values are below 1, with Hg having the highest TF of 0.92. This suggests that *S. alterniflora* primarily accumulates heavy metals in its underground parts and has lesser ability to transfer them upward. The plant appears to possess greater transportation capability for Hg. All values are below 1, with Hg having the highest TF of 0.92. This suggests that *S. alterniflora* primarily accumulates heavy metals in its underground parts and has lesser ability to transfer them upward. The plant appears to possess greater transportation capability for Hg. The average values, from high to low, are as follows: Zn (4.38)> Cd (2.54)> Pb (2.41)> Ni (2.09)> Cr (1.65)> Hg (1.54)> As (1.38)> Cu (1.30) (Figure 4B). All values are above 1 with Zn, Cd, Pb, and Ni having TFs above 2. This indicates that *S. glauca* possesses robust heavy metal TFs and relatively greater potential for the migration of Zn, Cd, Pb, and Ni. Consequently, these heavy metals can accumulate to high levels in the plant's above-ground parts, and its remnants may reintroduce them into the soil (Weis and Weis, 2004). Compared to *S. alterniflora*, *S. glauca* exhibits much higher TFs for heavy metals, with some variations in the order of transfer ability for different elements. This difference can be attributed to the transfer mechanism of heavy metals in plants, as well as to the unique properties of different plant species and environmental conditions in various research locations. *S. glauca* grows in a wetland area of non-flooded zones within the embankment, characterized by low pH and high salinity, which facilitates the migration of heavy metals from the underground parts to the above-ground parts. Meanwhile, *S. alterniflora* grows in a wetland area of the intertidal zone outside the embankment, where flooding may weaken its

TABLE 3 CR and TCR of some heavy metals in different parts of plants

Plant species	Parts	CR					TCR
		Cd	Cr	As	Pb	Ni	
S. alterniflora	SAU	1.22×10^{-8}	4.23×10^{-6}	8.33×10^{-8}	7.14×10^{-10}	2.04×10^{-7}	4.53×10^{-6}
	SAD	5.49×10^{-8}	9.04×10^{-6}	5.14×10^{-7}	2.62×10^{-9}	5.78×10^{-7}	1.02×10^{-5}
S. glauca	SSU	2.14×10^{-7}	5.62×10^{-6}	9.81×10^{-8}	1.79×10^{-9}	3.74×10^{-7}	6.31×10^{-6}
	SSD	7.93×10^{-8}	4.56×10^{-6}	7.47×10^{-8}	7.14×10^{-10}	1.7×10^{-7}	4.88×10^{-6}

ability to transport heavy metals within the plant (Weis and Weis, 2004; Yang et al., 2008).

In summary, the comparative analysis of BAFs and TFs for *S. alterniflora* and *S. glauca* indicates that *S. alterniflora* exhibits superior enrichment effects for Cr, Cd, and Zn, while *S. glauca* possesses strong enrichment abilities for Cr, Cd, Cu, and Zn, suggesting that *S. glauca* could potentially become a hyperaccumulator for these four heavy metals. However, *S. glauca* exhibits lower accumulation abilities for other heavy metals and does not display hyperaccumulation characteristics. Generally, a vital feature in identifying hyperaccumulator plants is that their transfer factors are greater than or equal to 1. Additionally, a concentration factor greater than 1 is also a crucial criterion in determining hyperaccumulator plants (Siyar et al., 2022). Although there is no clearly defined limit for heavy metal content, it is generally believed that hyperaccumulator plants need to contain at least 100.0 mg/kg of Cd, 10,000 mg/kg of Zn, and 1,000 mg/kg of other heavy metals such as Cu, Pb, and Ni to exhibit hyperaccumulation properties. However, it is important to note that these reference values may vary depending on factors such as the plant species, the specific heavy metal, and the environmental conditions under which the plant is grown (Brooks et al., 1977). *S. alterniflora* exhibits a concentration factor that surpasses 1 for Cr, Cd, and Zn, while the transfer factors for these heavy metals remain less than 1. Similarly, *S. glauca* displays concentration and transfer factors greater than 1 for Cr, Cd, Cu, and Zn, but the concentrations of these heavy metals in the plant are beneath the hyperaccumulator reference values because the soils in the research area have relatively low concentrations of heavy metals. Thus, additional experiments are necessary to verify whether *S. glauca* can be categorized as a hyperaccumulator plant. Furthermore, both *S. alterniflora* and *S. glauca* have a relatively low capacity for Pb enrichment, rendering them unsuitable for ecological restoration in regions with high Pb concentrations. In general, both *S. alterniflora* and *S. glauca* exhibit a certain level of purification against heavy metals such as Cr, Cd, Cu, and Zn in wetlands. Additional practical applications are crucial to confirm their effectiveness in wetland heavy metal purification. *S. alterniflora* can prevent heavy metals from spreading to the ocean by accumulating specific heavy metals, hence reducing the ecological risk of heavy metal concentration in the ocean (Gao et al., 2016). *S. alterniflora* and *S. glauca* demonstrate a measure of effectiveness in purifying heavy metals such as Cr, Cd, Cu, and Zn in wetland environments. Additional practical applications are required to validate their efficacy in heavy metal purification. *S. alterniflora* may be employed to mitigate the spread of specific heavy metals to the ocean by accumulating them, ultimately decreasing the ecological risk posed to the marine environment.

3.2 Health risk assessment of heavy metals in plants

Calculate the target hazard quotients and the total target hazard quotients of heavy metals in plants according to Eqs 4, 5. The health risk evaluation of *S. alterniflora* and *S. glauca* analyzed the individual risks for different parts, which are listed in Table 2. The target hazard quotients for eight heavy metals in the above-ground part of *S. alterniflora* (SAU) were arranged in descending order as Cr > As > Pb > Ni > Cu > Zn > Cd > Hg, while the below-ground part (SAD) ranked as Cr > As > Pb > Cu > Ni > Zn > Cd > Hg. The target hazard quotients for each heavy metal were similar in both parts. The THQ values for all eight heavy metals in the above-ground part were less than 1, with Cr having the highest value of 0.846. The results suggest that heavy metal exposure in the above-ground part of *S. alterniflora* does not pose a risk to human health. However, the THQ value for Cr was 1.808 and for As was 1.143 in the below-ground part, indicating that only Cr and As in the below-ground part of *S. alterniflora* may potentially be harmful to human health.

As presented in Figure 5, the target hazard quotient distribution for each heavy metal in the above-ground area of *S. glauca* (SSU) was arranged in a descending order as Cr>As>Cd>Pb>Cu>Zn>Ni>Hg. Meanwhile, in the below-ground part (SSD), the ranking order was Cr>As>Cu>Cd>Pb>Ni>Zn>Hg. The heavy metal ranking order in terms of the target hazard quotient was essentially the same in both the above-ground and below-ground areas. The THQ value of Cr was the highest in both the above-ground and below-ground parts of *S. glauca*, with a value of 1.124 for the above-ground area and less than 1 for the other seven heavy metals in both areas. These findings imply that only Cr in the above-ground area of *S. glauca* may present a potential health risk to humans, while other heavy metals do not appear to pose a risk.

Furthermore, the composite target hazard quotient for heavy metals in the above-ground and below-ground components of *S. alterniflora* and *S. glauca* was analyzed. The results indicated that the composite target hazard quotient for *S. alterniflora* was SAD (3.095) >SAU (1.074). Likewise, the composite target hazard index for *S. glauca* was SSU (1.479) >SSD (1.135). These findings demonstrate that the relationship between the composite target hazard quotient of heavy metals in different parts was not consistent across the two plant species. Additionally, all index values were greater than 1, and the contribution of Cr to the TTHQ value in all plant parts was the highest. This suggests that both plants may pose a potential health risk to humans due to the influence of Cr.

Calculate the carcinogenic risk and the total carcinogenic risk of heavy metals in plants according to Eqs 6, 7. The carcinogenic risk of the two plants as useable resources is shown in the Table 3. In terms of individual heavy metals, whether it is different plants or different parts of the same plant, he highest carcinogenic risk of the five heavy metals is Cr and the lowest is Pb, and only the CR of Cr is greater than 10^{-6}, which is within the tolerable range of human beings ($10^{-6} \leq$ TCR/CR $< 10^{-4}$), while the other heavy metals are less than 10^{-6}, which is considered to be no risk ($10^{-4} \leq$ TCR/CR). In terms of TCR, the above-ground and below-ground parts of *S. alterniflora* and *S. glauca* had TCRs ranging from 4.5×10^{-6} to 1×10^{-5}, with the largest being the below-ground part of *S. alterniflora* and the smallest being the above-ground part of *S. alterniflora*, which were within the tolerable range for human beings. These results indicate that both plants have some carcinogenic risk when used as edible resources, and that the carcinogenic risk is mainly caused by the heavy metal Cr, but is within the human tolerable range.

Therefore, the utilization of *S. alterniflora* and *S. glauca* cultivated in the study area as human food may pose potential health risks, but the carcinogenic risk is low. In particular, consumption of the underground part of *S. alterniflora* may have the highest health hazards for humans, mainly due to the significant contribution of Cr and as that pose high health risks. The composite target hazard quotient values of the above-ground and underground parts of *S. alterniflora* and *S. glauca* were slightly higher than 1, indicating that caution must be exercised in the development of food. The overall composite target hazard quotient of *S. alterniflora* was higher than that of *S. glauca*. The high single heavy metal health risk index values of Cr and as caused some plants to exceed the composite target hazard quotient. Since the Igeo indicates that the Tiaozini Wetland is not contaminated by human beings, these results are primarily due to the ability of these plants to accumulate heavy metals.

4 Conclusion

(1) The heavy metal accumulation in the below-ground part of *S. alterniflora* was higher than that in the above-ground part, while *S. glauca* is the opposite. The average concentrations of Cr, Cu, and Zn in both *S. alterniflora* and *S. glauca* were relatively high, which may be related to the essential elements required for their biological activities.
(2) Both plant species demonstrated a certain capacity to accumulate some heavy metals and had a certain purifying effect on heavy metal pollution in wetland environments, particularly Cr, Cd, Cu, and Zn. And *S. alterniflora* transported most of heavy metals to its below-ground part, while *S. glauca* accumulated the majority of heavy metals in its above-ground part.
(3) The composite target hazard quotient of both the above-ground and below-ground parts of both plants was greater than 1, which may pose a certain threat to human health if consumed in large amounts, but the carcinogenic risk is low.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

GL: Investigation, Conceptualization, Data curation, Formal Analysis, Writing–original draft, Writing–review and editing. ZC: Data curation, Investigation, Writing–original draft. SH: Conceptualization, Investigation, Writing–review and editing. ZS: Formal Analysis, Writing–review and editing. YZ: Methodology, Writing–review and editing. ZZ: Project administration, Writing–review and editing. RL: Investigation, Writing–review and editing. SW: Resources, Supervision, Writing–review and editing.

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Conflict of interest

Author RL was employed by Yancheng Tiaozini Wetland Research Institute Co, Ltd.

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Publisher's note

Supplementary Material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2024.1299139/full#supplementary-material

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