RESEARCH ON THE ABSORPTION CAPACITY OF *SUAEDA HETEROPTERA* UNDER TIDAL CONDITIONS FOR HEAVY METALS

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Abstract. In order to explore the absorption capacity of *Suaeda heteroptera* for heavy metals in coastal wetlands under tidal conditions, a tidal simulation device for *Suaeda heteroptera* habitat was designed based on the field conditions of Red Beach in China to investigate the absorption capacity of *Suaeda heteroptera* at different growth stages for heavy metals. The results showed that the on-site data monitoring at the Red Beach of Panjin in China revealed that zinc had the highest detected values in the water, sediment, and *Suaeda heteroptera* samples, and the absorption of heavy metals followed the order of Zn > Pb > Cu. Under tidal simulation conditions, the maximum absorption values of copper, lead, and zinc by *Suaeda heteroptera* at different growth stages were in the order of Zn > Pb > Cu, with metal content of 59.72 mg/kg, 46.73 mg/kg, and 15.70 mg/kg, respectively. These findings were consistent with the trend observed in the on-site monitoring data, and the values in the early growth stage were higher than those in the later growth stage. This result reveals the absorption capacity of *Suaeda heteroptera* for heavy metals and provides a theoretical basis and data support for wetland ecological restoration.

Keywords: *heavy metals, absorption, environmental chemistry, ecological restoration, enrichment*

Introduction

Coastal wetlands refer to the transitional zones between marine and terrestrial ecosystems, where the water depth is less than 6 meters during low tide. They possess unique hydrological, soil, vegetation, and biological characteristics, forming complex and specialized ecosystems. As a complex and critical zone with strong interactions across multiple layers and zones, coastal wetland ecosystems are characterized by frequent interactions among landforms, geofluids, and biogeochemical processes. They play a significant role in mitigating and adapting to climate change and providing essential services for the development of human society (Chang et al., 2019; Huang et al., 2020).

With the rapid development of industry and technology, heavy metal pollution has become a prominent type of pollution in wetlands (Carrillo et al., 2021). Heavy metal pollution is characterized by its difficulty in migration, long persistence, strong concealment, and high toxicity, making it challenging to eliminate (Lin et al., 1998; Yang et al., 2020; Cui et al., 2022). Heavy metals undergo migration and transformation processes such as surface runoff, absorption, and adsorption, depositing and releasing in wetlands, causing irreversible impacts on ecosystems and human society (Mattina et al., 2003; Cui et al., 2011; Bai et al., 2011). Common types of heavy metal pollution include Cu, Zn, Pb, Cd, among others (Hernández-Crespo and Martin, 2015). In the

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surface sediments of the Yellow River Delta wetland, Cu, Pb, and Cd were detected, with Cd being the primary potential ecological risk factor (Chen et al., 2023). Currently implemented ecological restoration measures, such as biological adsorption, are crucial for the recovery of disturbed wetlands (Renzi et al., 2019). Plant leaves have a strong capacity to absorb heavy metals from the atmosphere, while roots exhibit strong absorption capacity for heavy metals in water and sediments (Romera et al., 2007; Shahid et al., 2017). In a study by Lutts et al. (2016) *Kosteletzkya pentacarpos* was used to absorb Cd and Zn from water, with a Zn absorption efficiency of 56.9%.

Suaeda heteroptera is an annual herbaceous plant belonging to the family Amaranthaceae. It exhibits strong resistance to high salinity environments and heavy metals (Wang et al., 2018). Furthermore, *Suaeda heteroptera* demonstrates strong adaptability in wetland habitats and can be utilized for heavy metal absorption in coastal wetlands to maintain ecosystem stability. Existing literature has demonstrated the ability of *Suaeda heteroptera* to absorb heavy metals under soil cultivation conditions. However, the influence of tides on this absorption process remains unreported and requires further exploration.

Therefore, based on field monitoring data from the Liaohe Estuary wetland in China, this study designs a tidal simulation device to recreate the tidal environment of coastal wetlands and investigate the absorption capacity of *Suaeda heteroptera* for heavy metals. The aim is to provide a theoretical basis for the remediation of heavy metal pollution in wetlands.

Materials and methods

Heavy metal monitoring at the Red Beach of Panjin

Experimental materials

Main instruments: Flame atomic absorption spectrophotometer (Shimadzu AA-6880, Shimadzu, Kyoto, Japan, equipped with ASC-6880 automatic sampler, Shimadzu,Kyoto, Japan); Hollow cathode lamps for copper, lead, and zinc(Shimadzu (Shanghai) Experimental Equipment Co., Ltd); Centrifuge; Analytical balance; Commonly used laboratory instruments.

Main Reagents: Copper standard stock solution, bromocresol green indicator solution, hydrochloric acid, ammonia solution, ammonium pyrrolidinedithiocarbamate (APDC) - sodium diethyldithiocarbamate (DDTC-Na) mixed solution, hydrogen peroxide; Lead standard stock solution, nitric acid, perchloric acid, acetic acid, methyl isobutyl ketone (MIBK), ammonium acetate solution, ascorbic acid, potassium iodide solution; Zinc standard stock solution, ammonium acetate solution.

Sample collection

At the the Red Beach of Panjin site, sea water samples, sediment samples, and *Suaeda heteroptera* plant samples were collected at six sampling stations according to *Figure 1*. At each station, three random points were selected. Surface water samples were collected using a water sampler and transferred to sampling bottles. Sediment samples were collected using a sediment sampler at intervals of 10 cm. *Suaeda heteroptera* plant samples were carefully collected via hand-held shovel, once a month from April to August, ensuring the intactness of plants at different growth stages.

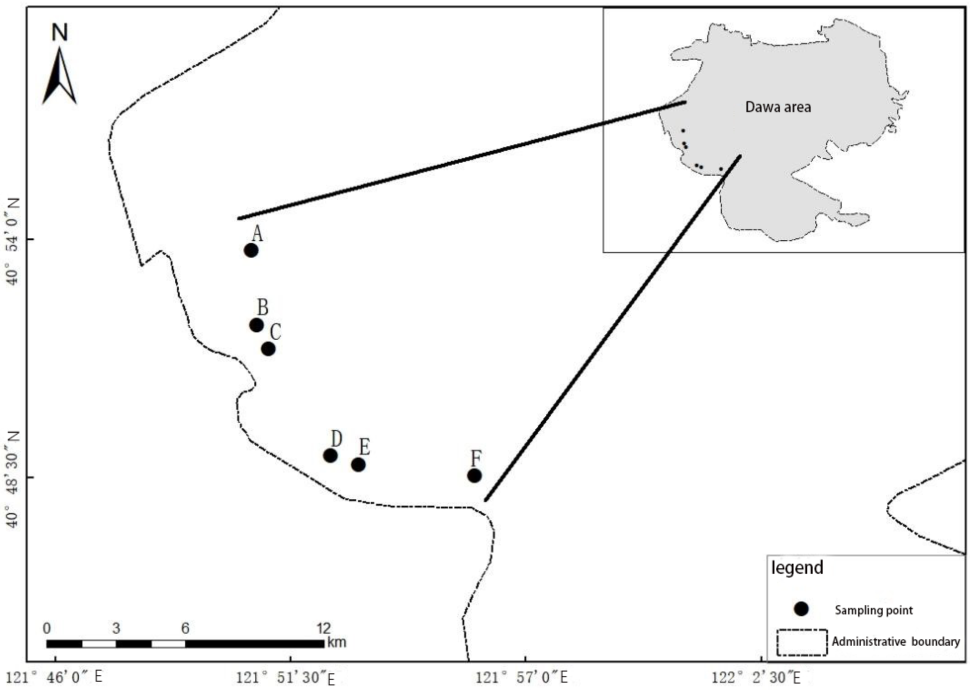

Figure 1. *Schematic diagram of distribution of sampling stations in the Red Beach of Panjin*

Analysis and detection method

The determination of heavy metals in this experiment was performed using flame atomic absorption spectrophotometry.

Method for seawater sample treatment: The heavy metals were dissolved by chelation using sodium diethyldithiocarbamate (DDTC) and ammonium pyrrolidinedithiocarbamate (APDC). Subsequently, the heavy metals were extracted and separated using methyl isobutyl ketone (MIBK).

Method for soil and plant sample treatment: The samples (The whole plant, including roots, stems and leaves) were weighed into microwave digestion vessels and hydrofluoric acid, nitric acid, and hydrochloric acid were added. The digestion was carried out according to the predetermined program. After digestion, the samples were cooled, acid was evaporated on a hot plate until nearly dry, and then 1% nitric acid solution was added to make up the volume. Insoluble materials were filtered out before analysis.

Data analysis and processing

The obtained data were analyzed using the following formula (*Eq.1*) to calculate the heavy metal content in the *Suaeda heteroptera* samples:

$$\omega = \frac{\rho v}{M} \tag{Eq.1}$$

where:

ω is the content of heavy metals in the dried *Suaeda heteroptera* sample (mass fraction),
ρ is the concentration of heavy metals obtained from the standard curve (μg/mL).

V is the volume of the sample preparation solution (mL).
M is the weight of the sample taken (g).

In this study, all data were analyzed and processed using Microsoft Office Excel 2007, and the results were presented in graphical form using origin2018.

Monitoring of absorption capacity of Suaeda heteroptera under tidal conditions

Experimental materials

Suaeda heteroptera seeds, the Red Beach of Panjin soil.

Experimental device

Figure 2 depicts the tidal simulation experimental setup. The tidal device measures were 60×60×205 cm, the water storage tank measures was 60×60×30 cm, and the planting area measures was 60×60×25 cm. The water storage tank has a capacity of 100 liters, and the planting area has pore radius of 0.9 cm.

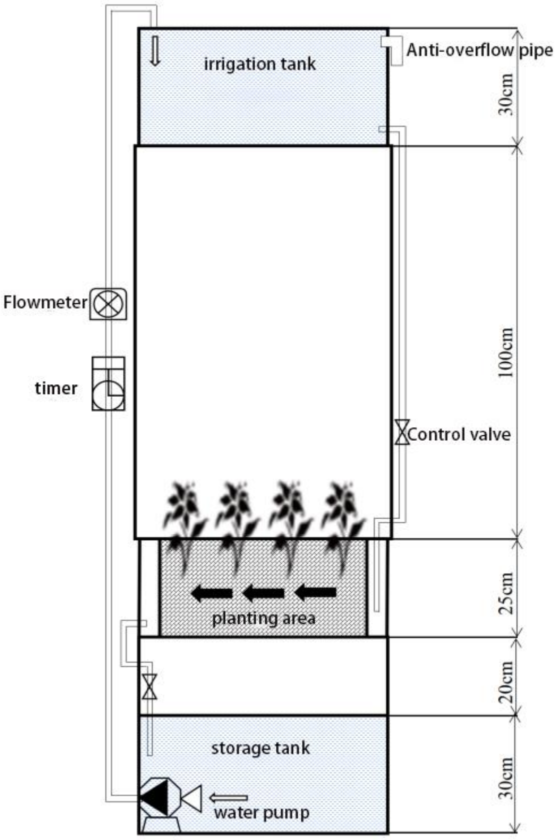

Figure 2. *Plan view of tidal simulation experimental device*

The tides in the surrounding waters of Panjin are irregular semi diurnal mixed tides, with two daily highs and two daily lows. Therefore, to simulute the tidal conditions, set the start time and water flow speed of the simulation device's water pump, with a rising tide time of 5 h, a retention time of 1 h, a falling tide time of 5 h, a retention time of 1 h, twice a day.

Analysis and detection method

The analysis and detection methods refer to Heavy Metal Monitoring at the Red Beach of Panjin.

Experimental procedure

A simulated habitat device for *Suaeda heteroptera* was designed and established to mimic tidal processes. The duration of the flood tide was set to 8 hours, ebb tide to 8 hours, and slack tide to 8 hours. *Suaeda heteroptera* was cultivated using soil-based cultivation in the device, with a soil cover depth of 2-3 cm. The salinity was set around 20, and the water flow valve controlled the tidal water depth at 6 cm. In late May (early growth stage of *Suaeda heteroptera*), when the plants were in a healthy condition, circulating water with a seawater composition was used, and the concentrations of heavy metals in the water were set to Cu:Pb:Zn = 50:50:100 μg/L. In early July (late growth stage of *Suaeda heteroptera*), with the plants still in a healthy condition, the concentrations of heavy metals in the water were adjusted to Cu:Pb:Zn = 100:100:200 μg/L, while keeping other conditions constant. Samples were collected every 3 days to measure the heavy metal content in *Suaeda heteroptera* plants and the circulating water.

Photo of the experimental culture or equipment

The following are the experiment photo of the tide simulation device and the photo of the plants in the device (*Photos 1,2*).

Photo 1. *Experiment photos of the tide simulation*

Photo 2. *Experiment photo of the plants in the device*

Data analysis and processing

Data analysis and processing refer to Heavy Metal Monitoring at the Red Beach of Panjin.

Results

Heavy metal content in surface seawater at the Red Beach of Panjin

Based on *Figure 3*, the copper (Cu) content in seawater is low, with the highest value observed in July and the lowest value in March. According to the "Seawater Quality Standard (GB 3097-1997)," the water quality at some stations slightly exceeds the Class I water quality standard.

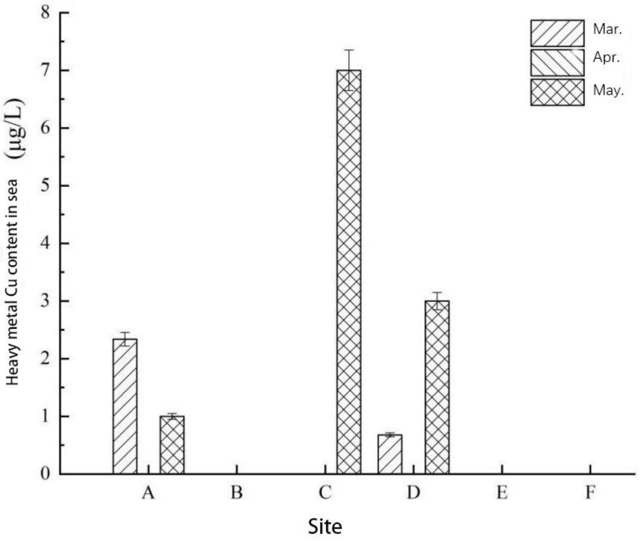

Figure 3. *Pollution of heavy metal Cu in seawater at different stations in the Red Beach of Panjin site*

Based on *Figure 4*, the lead (Pb) content shows little variation with respect to the months. The overall highest value was observed in April, while the lowest value was observed in March. According to the "Seawater Quality Standard (GB 3097-1997)" all stations in July meet the Class III water quality standard with lead content below 10 μg/L, which is within the water quality standard for coastal scenic tourist areas. The data for April indicate slightly higher lead content, with most stations exceeding the Class III water quality standard.

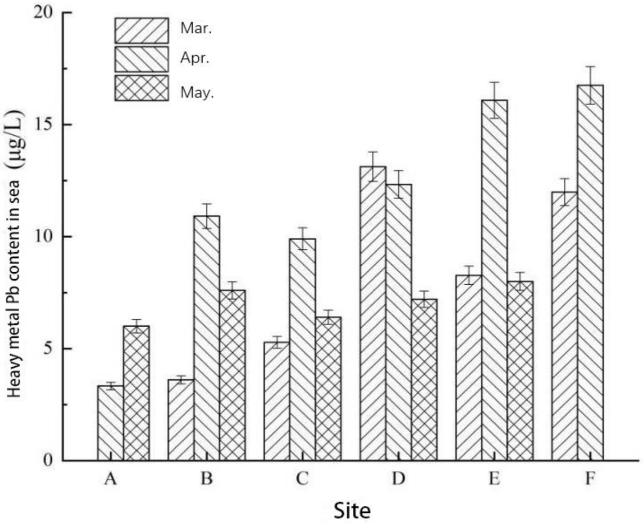

Figure 4. *Pollution of heavy metal Pb in seawater at different stations in the Red Beach of Panjin site*

According to *Figure 5*, the zinc (Zn) content shows significant fluctuations, with higher concentrations observed during the summer compared to the spring. The overall maximum concentration occurred in July, while the minimum concentration occurred in April. According to the "Water Quality Standard for Seawater (GB 3097-1997)" the zinc concentrations at different sampling stations during different periods are all below the Class I water quality standard of 20 μg/L for heavy metals.

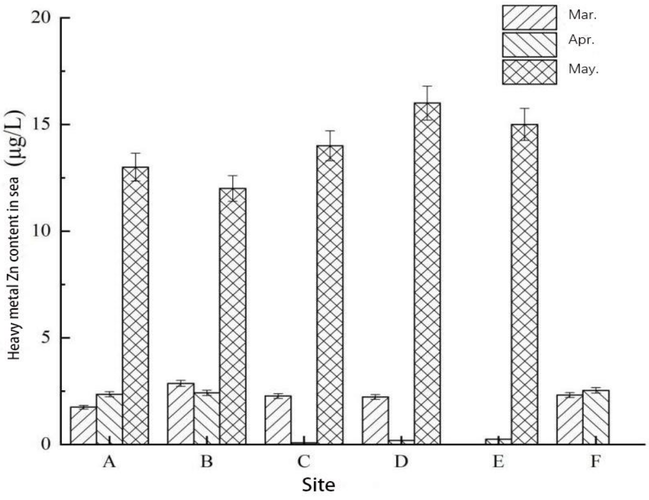

Figure 5. *Pollution of heavy metal Zn in seawater at different stations in Red Beach site*

Heavy metal content in surface sediments of Red Beach

Figure 6 shows the heavy metal content in surface sediments detected at Red Beach in November. Overall observations indicate that the copper (Cu) and lead (Pb) concentrations at various sampling sites exhibit no significant variations, while zinc (Zn) shows slight fluctuations. The zinc content is higher than that of copper and lead, with a small difference between copper and zinc concentrations. The average concentrations of these heavy metals are 26.48 mg/kg for copper, 79.99 mg/kg for zinc, and 33.52 mg/kg for lead. According to the "Quality Standard for Marine Sediments (GB 18668-2002)" the concentrations of copper, zinc, and lead at all sampling sites meet the Class I quality standard for marine sediments, satisfying the requirements of coastal scenic tourism areas.

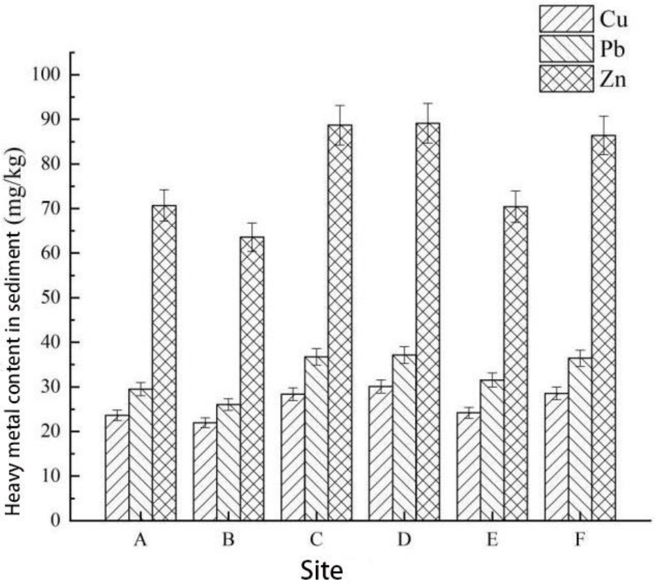

Figure 6. *Heavy metal pollution in sediments of different stations at the Red Beach of Panjin site in November*

Content of heavy metals in plants of Suaeda heteroptera in the Red Beach of Panjin

Figure 7 presents the heavy metal content in *Suaeda heteroptera* plants at Red Beach, detected in April, May, June, July, and August. Overall, the copper (Cu) content in *Suaeda heteroptera* plants shows insignificant variations over time, ranging from 5.39 mg/kg to 7.42 mg/kg with an average of approximately 6.45 mg/kg. On the other hand, the zinc (Zn) content in *Suaeda heteroptera* plants is high and exhibits significant fluctuations over time, ranging from 11.37 mg/kg to 38.1 mg/kg with an average of 24.74 mg/kg. In comparison, the lead (Pb) content in *Suaeda heteroptera* plants is the lowest among the three heavy metals, with an average content below 3 mg/kg.

Figure 8 presents the heavy metal content in *Suaeda heteroptera* plants at six sampling points at Red Beach in November. Overall observations indicate that the heavy metal content in *Suaeda heteroptera* plants is significantly higher than the average values observed in April to August. Among the different heavy metals, lead content remains the lowest, while zinc content remains the highest. Among the sampling points, the highest concentrations of copper, lead, and zinc are recorded at

Point A, with values of 27.59 mg/kg, 21.47 mg/kg, and 73.65 mg/kg, respectively. The lowest concentrations are observed at Point D, with values of 11.47 mg/kg, 8.38 mg/kg, and 25.88 mg/kg for copper, lead, and zinc, respectively. The average concentrations of these heavy metals are 20.04 mg/kg for copper, 15.58 mg/kg for lead, and 49.69 mg/kg for zinc.

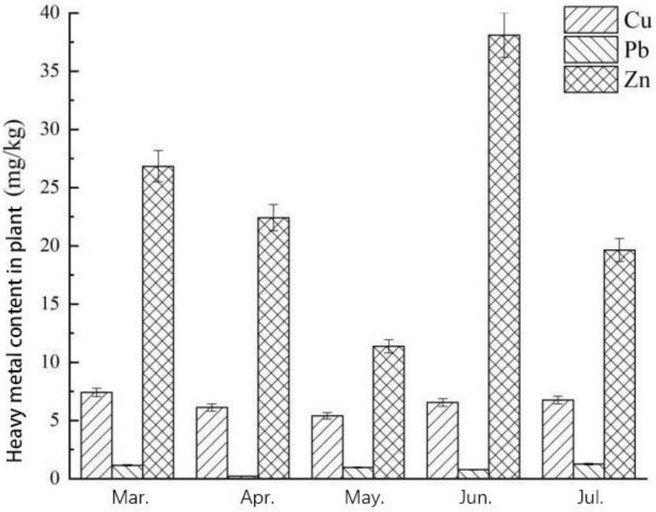

Figure 7. *Heavy metal pollution of Suaeda heteroptera in the Red Beach of Panjin site*

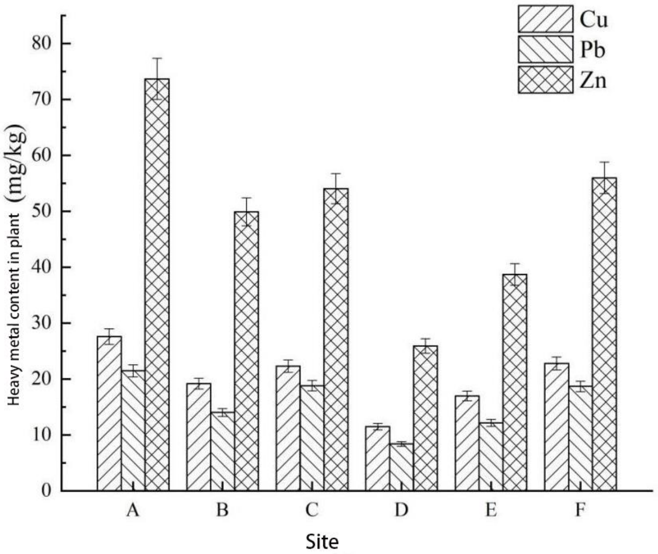

Figure 8. *Heavy metal pollution of Suaeda heteroptera at different stations in the Red Beach of Panjin in November*

Experimental results of tidal simulation device

Figure 9 shows the variation of copper (Cu), lead (Pb), and zinc (Zn) concentrations in the water under tidal simulation conditions in May. The concentrations of copper and zinc in the water exhibit an overall increasing trend followed by a decrease over time. On the other hand, the concentration of lead initially decreases and then increases, reaching its peak at the same time as copper and zinc. The maximum concentrations of copper, lead, and zinc in the water are observed on 23rd May, with values of 134 μg/L, 93.4 μg/L, and 174 μg/L, respectively. The minimum concentrations of copper and zinc occur on 17th May, with values of 61 μg/L and 45 μg/L, respectively. Unlike copper and zinc, the minimum lead concentration is observed on 20th May, with a value of 23.50 μg/L.

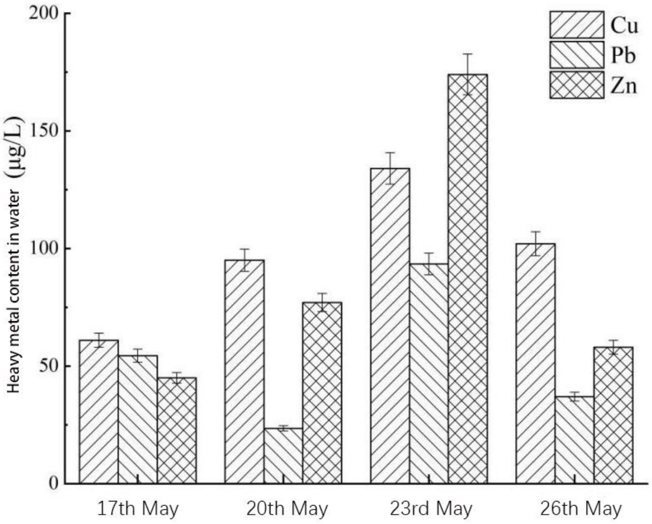

***Figure 9.** Changes of heavy metal content in water under tidal simulation in May*

Figure 10 shows the variation of copper (Cu), lead (Pb), and zinc (Zn) concentrations in the water under tidal simulation conditions in July. The concentrations of copper, lead, and zinc in the water exhibit an overall decreasing trend initially, reaching their minimum values, followed by a slight increase. The maximum concentrations of copper, lead, and zinc in the water are observed on July 7, with values of 151 μg/L, 8.41 μg/L, and 190 μg/L, respectively. The minimum concentrations of copper, lead, and zinc occur on July 13, with values of 41 μg/L, 0.41 μg/L, and 45 μg/L.

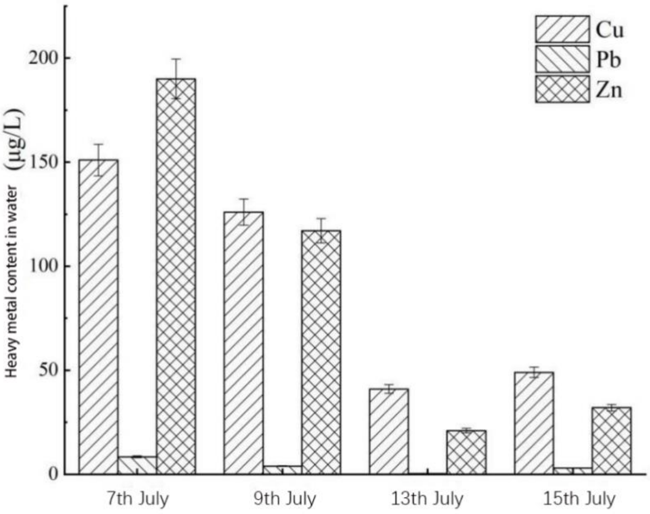

***Figure 10.** Changes of heavy metal content in water under tidal simulation in July*

Figure 11 shows the variations in the concentrations of heavy metals copper, lead, and zinc in plant tissues under tidal simulation conditions in May. The overall trend of copper and zinc concentrations in the plant tissues is a gradual decrease followed by an increase, ultimately reaching maximum values in the same time. On the other hand, the lead concentration initially increases and then decreases to its minimum value, coinciding with the time when copper and zinc reach their maximum values for the month. The maximum concentrations of copper, lead, and zinc in the plant tissues are observed on May 26, with concentrations of 15.70 mg/kg, 46.73 mg/kg, and 59.72 mg/kg, respectively. The minimum concentrations of copper and lead occur on May 23, with concentrations of 7.09 mg/kg and 15.84 mg/kg, respectively. In contrast, the minimum concentration of zinc is observed on May 20, with a concentration of 34.38 mg/kg.

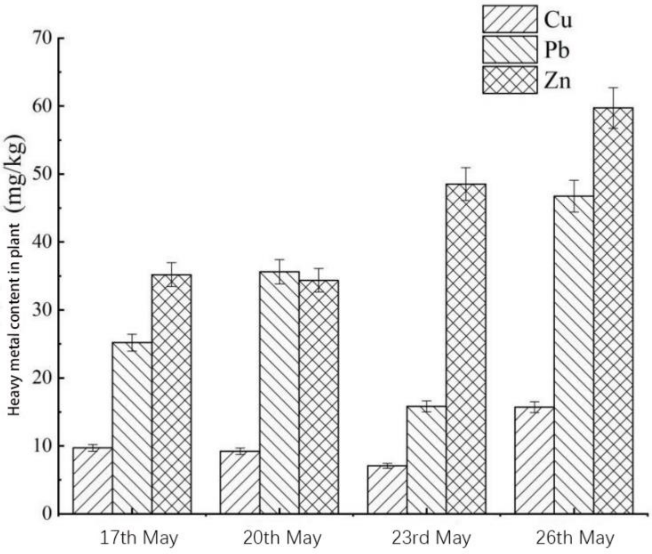

Figure 11. *Changes of heavy metal content in plants under tidal simulation in April*

Figure 12 illustrates the changes in the concentrations of heavy metals copper, lead, and zinc in plant tissues under tidal simulation conditions in July. The overall trend for copper and zinc concentrations in the plant tissues is an initial increase, reaching their respective maximum values, followed by a gradual decrease, and ultimately reaching their minimum values simultaneously. In contrast, the lead concentration initially decreases and then increases, coinciding with the time when copper reaches its maximum value for the month. The maximum concentrations of copper and lead in the plant tissues are observed on July 13, with concentrations of 13.67 mg/kg and 19.35 mg/kg, respectively. The maximum concentration of zinc occurs on July 9, with a concentration of 44.41 mg/kg. The minimum concentrations of copper, lead, and zinc in the plant tissues are all observed on July 15, with concentrations of 6.19 mg/kg, 3.48 mg/kg, and 15.91 mg/kg, respectively.

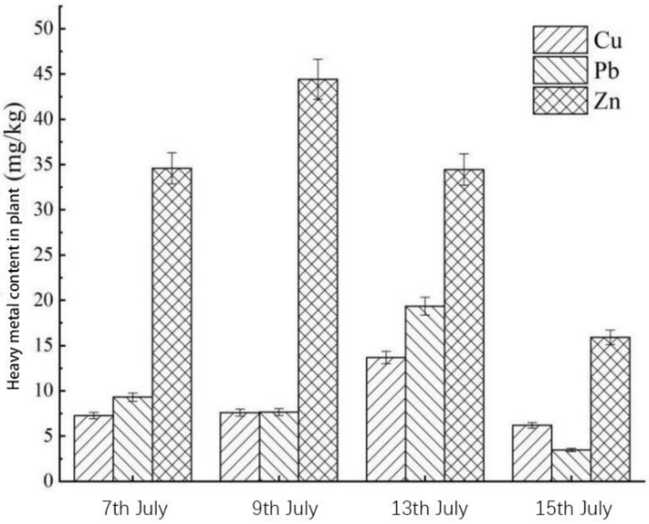

Figure 12. *Changes of heavy metal content in plants under tidal simulation in July*

Discussion

The overall distribution of various heavy metals in sediments at different sites shows the order of zinc > lead > copper, which is consistent with the results of soil surveys conducted by research (Fan et al., 2018) at the Red Beach of Panjin. Sediments are also susceptible to external environmental factors, such as changes in physicochemical properties at the water-sediment interface, which can lead to the re-release of bound heavy metals into the water and trigger secondary pollution (Moreno-González et al., 2022).

In autumn, the average content of heavy metals in the *Suaeda heteroptera* is higher than in spring. The reason for this is that during the transition from spring to autumn, the *Suaeda heteroptera* is still in its growing phase and continues to accumulate heavy metals. By autumn, it reaches the fully mature stage, and the content of heavy metals reaches its highest value and did not increase further.

From the germination period to the mature stage of *Suaeda heteroptera*, the concentrations of heavy metals in the plant tissues consistently follow the order of zinc > lead > copper, mirroring the trend observed in the sediment samples. This suggests that the levels of heavy metals in sediments can to some extent determine the total uptake of heavy metals by *Suaeda heteroptera*. This finding is in line with the research (Zhu et al., 2005), which showed that the accumulation of Cu, Zn, Pb, and Cd in plants followed the order of Zn > Pb > Cu > Cd, with corresponding bioaccumulation coefficients of 0.97, 1.73, 0.41, and 2.23. Another factor contributing to this pattern is that zinc is a trace element required for the growth and development of *Suaeda heteroptera*, leading to a higher uptake capacity for zinc compared to other heavy metals.

The trends of heavy metals copper, lead, and zinc in *Suaeda heteroptera* seedlings and the growth stage group were consistent, while the trends in the flowering and fruiting stage group were different (Zhu et al., 2006). It was observed through experiments that under the same suitable salt concentration, *Suaeda heteroptera* exhibited the highest dry weight and best growth when the water depth was 6 cm. When the burial depth was less than 4 cm, seed germination decreased with increasing soil depth, and when the burial depth exceeded 4 cm, seed germination was unsuccessful. Moderate salinity levels (10-20) were also more suitable for seed germination and plant growth (Wang et al., 2022). Since the seedling stage is influenced by external factors and exhibits significant variations in heavy metal content, we selected the growth stage of *Suaeda heteroptera* for the experiment to establish a simultaneous comparison with the hydroponic experiment.

According to the data from the tide simulation device in May, it was observed that there is a secondary pollution caused by the release of heavy metals from the soil into the water, which is consistent with the previous mentioned studies. During this period, *Suaeda heteroptera* is in its early growth stage, and its ability to absorb heavy metals gradually increases. As time passes, the rate of heavy metal absorption by *Suaeda heteroptera* balances with the rate of soil release. Eventually, the absorption rate exceeds the release rate, resulting in a decrease in heavy metal content in the water.

The data from the tide simulation device in July indicates that *Suaeda heteroptera* is in its late growth stage. During this period, the absorption rate of heavy metals by the plant should be higher than the release rate from the soil, leading to a decrease in heavy metal content in the water. However, since *Suaeda heteroptera* is almost mature at this stage, its ability to absorb various metal elements gradually weakens. Around the time of July 13th, *Suaeda heteroptera* reaches a saturation point in heavy metal absorption, causing an imbalance in the exchange of heavy metals between the water and the soil, resulting in an increase in heavy metal content in the water. Additionally, the accumulation of high concentrations of heavy metals in certain parts of *Suaeda heteroptera* may inhibit the plant's photosynthesis, thereby affecting the absorption of heavy metals within the plant.

In May, during *Suaeda heteroptera*'s early growth stage, the maximum content of heavy metals copper, lead, and zinc in the plant occurs in the late stage of May, with concentrations of 15.70 mg/kg, 46.73 mg/kg, and 59.72 mg/kg, respectively. The order of maximum metal content is zinc > lead > copper, which is consistent with the heavy metal content in the monitored sediment. In July, during *Suaeda heteroptera*'s late growth stage, the maximum content of copper and lead in the plant is 13.67 mg/kg and 19.35 mg/kg, respectively. Zinc shows the maximum content earlier, with a concentration of 44.41 mg/kg. The order of maximum metal content is zinc > lead > copper, which is consistent with the heavy metal content in the monitored sediment. Studies (Wang et al., 2020) on Canna indica growth showed a rapid growth followed by a slower growth, with the peak absorption of heavy metals occurring during the bud stage. The study (Nan et al., 2019) confirmed significant differences in harmful metal content in peonies at different stages, with a greater potential for early-stage absorption of harmful elements. Similarly, it can be inferred that *Suaeda heteroptera* has a stronger capacity to absorb heavy metals copper, lead, and zinc during its early growth stage. This may be due to the insufficient resistance mechanisms developed by *Suaeda heteroptera* against heavy metals during the early growth stage, resulting in a higher uptake of lead.

Conclusion

As a salt-tolerant, dominant plant, *Suaeda heteroptera* is insensitive to heavy metal pollution so can be used in wetland remediation and ecological restoration projects for heavy metal pollution. Currently, in the data analysis of the Red Beach of Panjin, zinc has the highest detection rate among the heavy metals. In the tidal simulation experiments, it was found that *Suaeda heteroptera* exhibited a higher absorption capacity for zinc compared to copper and lead, with the order of absorption capacity being zinc > lead > copper. Additionally, mature *Suaeda heteroptera* plants showed a significantly higher metal absorption capacity than those in the growth stage. Considering the influence of external environmental factors and the adaptation of *Suaeda heteroptera* to the high-salinity environment of coastal wetlands, it can be applied in the ecological restoration of mildly contaminated coastal wetlands with heavy metals. In practical applications, regulating the active oxygen metabolism of *Suaeda heteroptera* can be explored to enhance its absorption capacity for heavy metals. However, the specific methods and parameters for achieving this enhancement require further research.

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Conflicts of Interests. The authors declare no conflict of interests.

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