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Original Research

Study of the Long-term Treatment Effect of Constructed Wetlands for Acid Mine Drainage

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Abstract

Acid mine drainage (AMD) threatens water resources. Research on the treatment effect of heavy metals in AMD using constructed wetlands has been conducted, most often indoors and in short cycles. This study considered an AMD-constructed wetland that had operated for 12 years as the research subject. Water, sediments, and wetland plant samples were analyzed from different sampling points in the wetland to study the treatment effect of constructed wetlands on AMD and to explore the distribution characteristics of heavy metals in constructed wetlands. The results indicated that the constructed wetlands achieved removal rates of 97.59% for Fe and 83.05% for Mn in AMD. At the outlet of the wetlands, Fe, Mn, Cu, and Zn all met the Class III standard of "surface water environmental quality standards" (GB3838-2002). The content of heavy metals in the sediments was as follows: Fe>Mn>Zn>Pb>Cu>Cd. The contents of heavy metals in the rhizosphere sediments were higher than those in the non-rhizosphere sediments. The maximum concentrations of Fe, Mn, Cu, Zn, Pb, and Cd were 3.44, 10.67, 3.91, 3.50, 2.52, and 12.22 times that of the control group, respectively. Plants have a strong ability to accumulate heavy metals. Except for Mn, various elements were enriched in the surface areas of plant roots. The enrichment effect of rhizosphere sediments and plant surfaces is important in removing heavy metals from AMD.

Keywords: constructed wetlands, acid mine drainage, water, sediments, wetland plant

Introduction

The amount of wastewater discharged from mines due to mining reaches 1.2-1.5 billion tons in China annually [1]. The large amount of acidic mine drainage (AMD) generated during mining has become the main source of pollution in mining areas. The presence of AMD in surface rivers leads to a decrease in the pH value of the water, which can cause heavy metals in the water to exceed the standard. AMD has significant damage to aquatic ecosystems, as well as to human and animal water usage, agricultural irrigation, and other

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activities [2, 3]. High concentrations of heavy metals and severely acidic water are discharged into the water, which enhances the toxicity of the river, destroys the living environment of aquatic organisms, and reduces biodiversity [4]. At the same time, AMD is highly likely to penetrate the ground through karst conduits and then pollute groundwater, bringing safety risks to residents' drinking water. AMD discharge can cause soil acidification, and studies have shown that 15,000 hectares of land in Canada have been acidified by AMD [5]. The Dabaoshan area in China has a soil pH as low as 5.3 due to the effect of AMD [6]. There have been notable rises in the concentration of heavy metals in the soil of a Spanish mining region, including zinc (Zn), copper (Cu), arsenic (As), and lead (Pb) [7]. Therefore, AMD pollution is a global problem, and many domestic and international scholars have widely discussed it.

Traditional AMD treatment technologies use the addition of chemicals (e.g., lime, limestone, sodium hydroxide, or other alkaline substances) to improve the pH value of AMD through chemical reactions and then reduce the concentration of heavy metals [8]. Utilizing wetland systems to treat AMD represents a significant alternative to conventional chemical treatment approaches. Constructed wetlands realize the ecological purification of AMD through the physical and chemical reactions and biochemical processes generated by the coupling of substrates, plants, and microbial systems in the wetland system. This is achieved by inducing heavy metals to precipitate into sediments or to be absorbed and converted into constituents of wetland plants [9, 10]. Wetland substrates can provide a growth medium for plants and microorganisms and directly remove heavy metals through precipitation and adsorption. Studies have shown that 50% of heavy metals in wastewater can be adsorbed by suspended solids in wetland and wetland substrates [11]. Heavy metals entering the wetland system are filtered, retained by the substrate, and precipitated. This process is important for transferring heavy metals from the liquid to the solid phases in aqueous environments [12]. Wetland plants are an indispensable part of the constructed wetland treatment system.

Aquatic plants remove pollutants through their metabolic processes, and a series of positive effects are caused by changes in the root microenvironment and wetland sediments produced by this metabolism. These changes collectively contribute to the coordination of pollutant removal [13]. Plants can assimilate and absorb pollutants and accumulate them in their bodies to remove contaminants from the water body. Many plants in wetlands can absorb and accumulate heavy metals. Cattails can effectively enrich Fe and Mn in AMD [14]. The cadmium (Cd) uptake efficiency by duckweed can achieve a maximum of 91%, and for nickel (Ni), it can reach a peak of 50% [15]. Reed and Lychion demonstrated a commendable remediation effect on water bodies contaminated with cadmium (Cd), lead (Pb), copper (Cu), and zinc (Zn) [16].

Currently, wastewater treated by constructed wetlands is mostly domestic sewage or a certain type of high-concentration heavy metal in industrial wastewater, and most of the experiments are conducted indoors with a short experimental period. Nevertheless, research on establishing constructed wetlands in the wild to treat acid mine drainage is scarce, and even fewer studies have been conducted on the long-term treatment effects of constructed wetlands on AMD. Therefore, this study used a constructed wetland for 12 years to treat AMD as the research subject. The distribution characteristics of major pollutants in the wetlands were studied by sampling and analyzing the water, sediments, and plants of the wetland system. The study also determined the long-term treatment effects and removal pathways of heavy metals in AMD by constructed wetlands, aiming to provide support and reference for constructing field wetland purification systems.

Materials and Methods

Study Area

The study area was Chafan Village, Zhuchang Town, Guanshanhu District, Guiyang City, and Guizhou Province (Fig. 1). The concentrations of Fe and Mn at the AMD discharge outlet were relatively high, reaching 32.18 mg/L and 3.31 mg/L, respectively. After discharge, the AMD passes through a pre-reaction tank, reaction tank, sedimentation tank, constructed wetland, and clear water tank before being discharged downstream. The effluent from the sedimentation tank enters the constructed wetland system. The wetland is 100 m long, with a substrate material of porous active fillers composed of calcium carbonate and calcium silicate. It works in conjunction with plants (e.g., horsetail, *Equisetum ramosissimum*; annual bluegrass, *Poa annua L.*), which have well-developed aeration tissues. The system has been in operation for 12 years, and the wetland has shown a certain treatment effect on AMD, with the surface layer of the wetland matrix completely covered by sediments. The distribution of sampling points in this study is shown in Fig. 1.

Sample Collection and Analysis

Four sampling points were set up in the wetland, located at the inlet, the middle areas A and B (approximately 25 m apart), and the wetland outlet. The samples collected included water, sediments, and wetland plants. Water samples were drawn using a syringe, and 500 mL was placed into a polyvinyl chloride bottle, acidified with HNO_3, and then taken back to the laboratory. During water sampling, sediments from wetlands (rhizosphere, non-rhizosphere) and wetland plants (aboveground and belowground) were simultaneously sampled and analyzed. Sampling points for sediments were kept consistent with those for

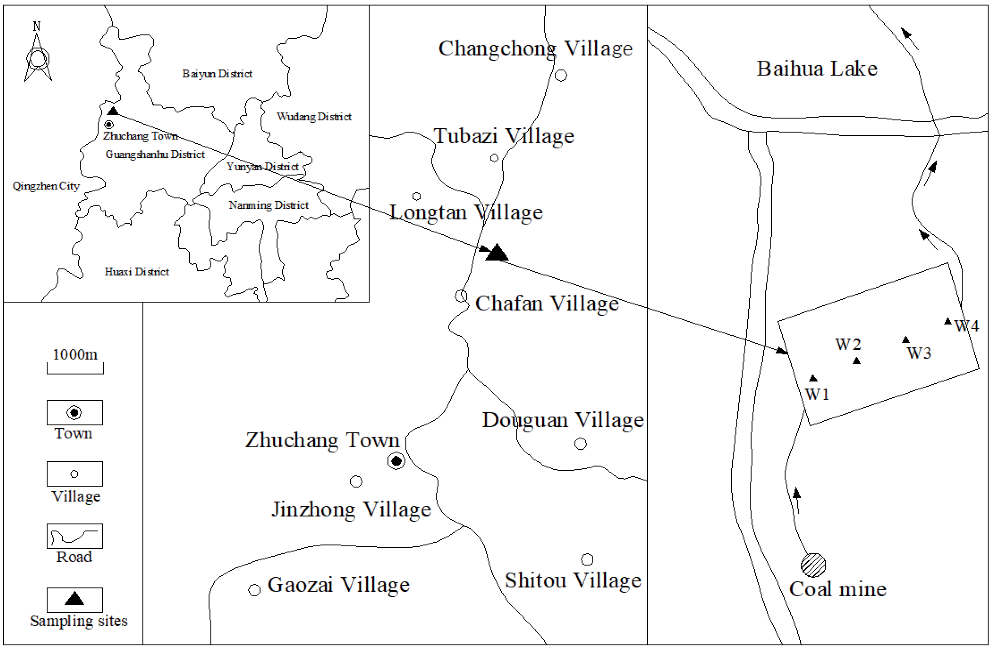

Fig. 1. The area and sample collection and distribution in the study.

water bodies. During sampling, the plant was carefully uprooted with a wooden shovel. The rhizosphere sediments were collected and placed in polyethylene bags. Finally, the samples were sealed immediately. Plants were separated into underground and aboveground parts and then returned to the laboratory after being numbered with the aforementioned sealed bags. Simultaneously, non-rhizosphere sediments were collected from 5-10 cm near the sampling site, where no plants were present, and sealed immediately. The rhizosphere and non-rhizosphere sediments in the sealed bags were centrifuged, freeze-dried, and sieved through a 20-mesh sieve (0.90 mm). Three replicates were obtained from each sampling location. Upon returning to the laboratory, the aboveground plants were thoroughly rinsed with tap water and then carefully cleaned with deionized water. The samples were placed in an oven at 105°C for 30 min, then dried at 60°C until reaching a constant weight and ground to a 100-mesh consistency for subsequent use.

Analysis Methods

The pH of the water was determined using a pH meter (PHSJ-3F type, Shanghai Rex). The sulfate (SO_4^{2-}) concentration in water was determined using barium chromate spectrophotometry. The content of heavy metals in plant roots is extracted using the DCB method [17]. The content of heavy metals in the aboveground parts, roots, and sediments was digested using the aqua regia reflux-long tube digestion-wet acid digestion method. The digestion solution and heavy metals in the water body were determined within seven days using an inductively coupled plasma atomic emission spectrometer (ICP-AES, Shimadzu ICPE-9820).

Data Analysis and Evaluation Methods

All data were analyzed using SPSS, with statistical significance determined by one-way ANOVA variance analysis. Origin2022 was used for mapping.

The evaluation of the water body adopted the Class III criteria outlined in the “Surface Water Environmental Quality Standard” (GB3838-2002). The bioconcentration factor (BCF) of heavy metals in plant stems, leaves, roots, and on the root surface, as well as the translocation factor (TF), were used to evaluate the accumulation and translocation characteristics of plants to heavy metals according to the following formulas:

$$BCF = \text{heavy metal concentration in plant (surface, root, shoot)/Heavy metal content in sediment rhizosphere}$$

$$TF_{root} = \text{heavy metal concentration in plant roots/heavy metal concentration on the plant root surface}$$

$$TF_{shoot} = \text{heavy metal concentration in plant stems and leaves/heavy metal concentration in plant roots}$$

Results

The Influence of Constructed Wetlands on pH, Sulfate, and DO in AMD

This research used constructed wetlands to purify AMD discharged from abandoned stone cavern coal mines. The pH changes at each sampling point are shown in Fig. 2a). The pH at the wetland entrance was 6.62, and then the pH at each sampling point increased

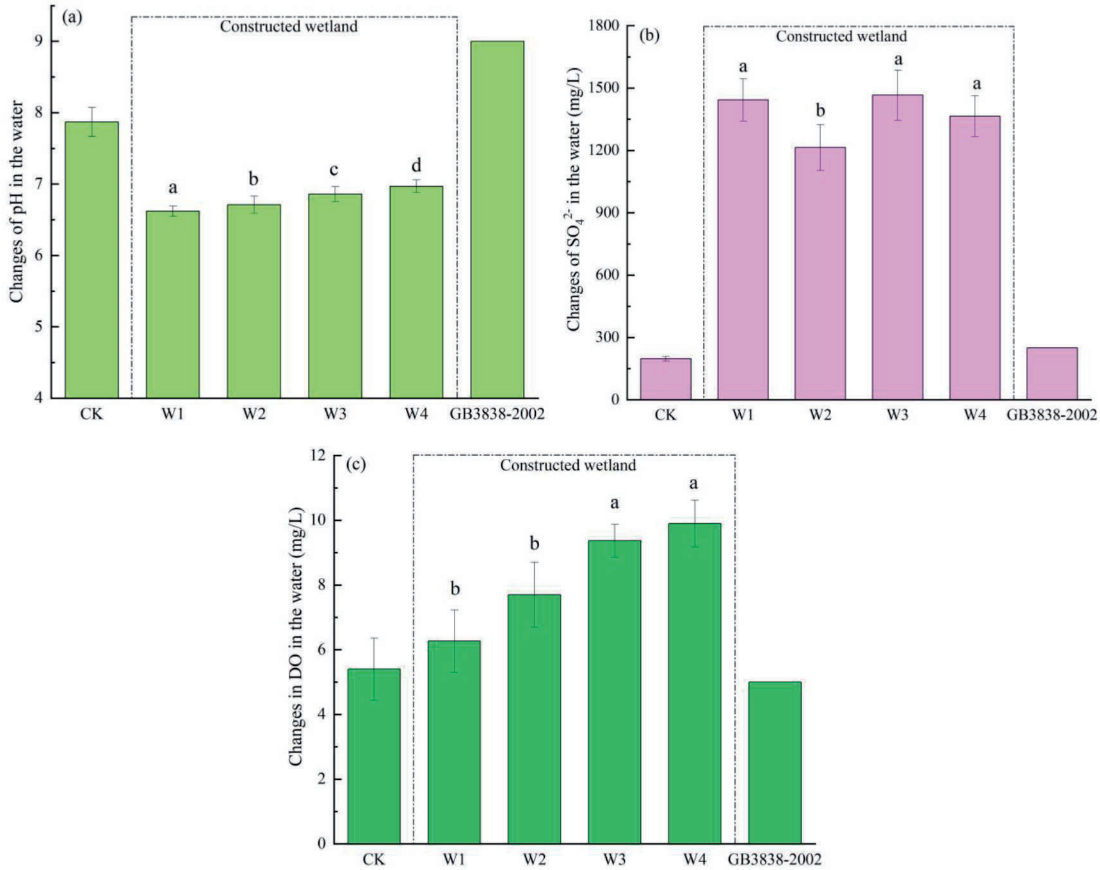

Fig. 2. Changes in a) pH, b) SO_4^{2-}, and c) DO in the water of the wetland. Different lowercase letters above the columns indicate significant differences among different sampling points (P<0.05), the same below.

to varying degrees. The pH value at W4 increased by 0.35 units compared with W1. Previous research has also indicated that plant growth can cause the pH of AMD to shift toward the neutral range [18]. Although the pH at each sampling point increased to varying degrees, all values remained below 7.87 for the control (CK). Additionally, the SO_4^{2-} concentrations in the wetland were 1214 to 1466 mg/L, much higher than those of CK (198 mg/L). According to the standard limits for Class III in the "surface water environmental quality standards" (GB3838-2002), the SO_4^{2-} in the constructed wetland system exceeded the standard by 4.86-5.86 times. This indicates that the SO_4^{2-} from AMD produced by an abandoned coal mine could have a certain impact on the downstream water of Baihua Lake. As the distance from the wetland entrance increased, the dissolved oxygen (DO) in the water increased to varying degrees, and the DO at the wetland outlet was significantly higher than at the entrance (P<0.05).

Purification Effect of Field-Constructed Wetland on Heavy Metals in AMD

The concentration of heavy metals at each sampling point in the constructed wetland treating AMD is shown in Fig. 3. There was a significant difference in Fe concentration among the sampling points (P<0.05), and it gradually decreased with the increase in distance from the wetland entrance. The Fe concentration at W4 was reduced by 97.59% compared with W1. Studies have shown that when the pH in AMD rises to 6, the concentration of Fe in the water will drop below 1 mg/L, and the removal rate of Fe can reach 99.9% [19]. The Fe concentration at the wetland outlet W4 dropped to 0.22 mg/L, which was higher than the Fe concentration at the CK point but lower than the concentration limit for Class III in the "surface water environmental quality standards" (GB3838-2002). This result indicated that the wetland has a good removal effect on Fe in AMD. Similar to Fe, the concentration of Mn in AMD also decreased by varying degrees, from 0.59 mg/L at the W1 point to 0.10 mg/L at the W4 point. Although the Mn concentration was significantly reduced, the Mn concentration at the wetland outlet was equal to the concentration limit. This result indicated that there was still a potential risk of Mn concentration exceeding the standard. As shown in Fig 3c) and d), the Cu and Cd concentrations in AMD were insignificant, and the concentrations of Cu and Cd at each point were higher than those at the CK point. Cd was much greater than the corresponding concentration limit, seriously impacting downstream water. Along the flow direction, the concentrations of Zn and Pb in the water significantly decreased. Compared with W1, the concentrations of Zn and Pb at point W4 decreased

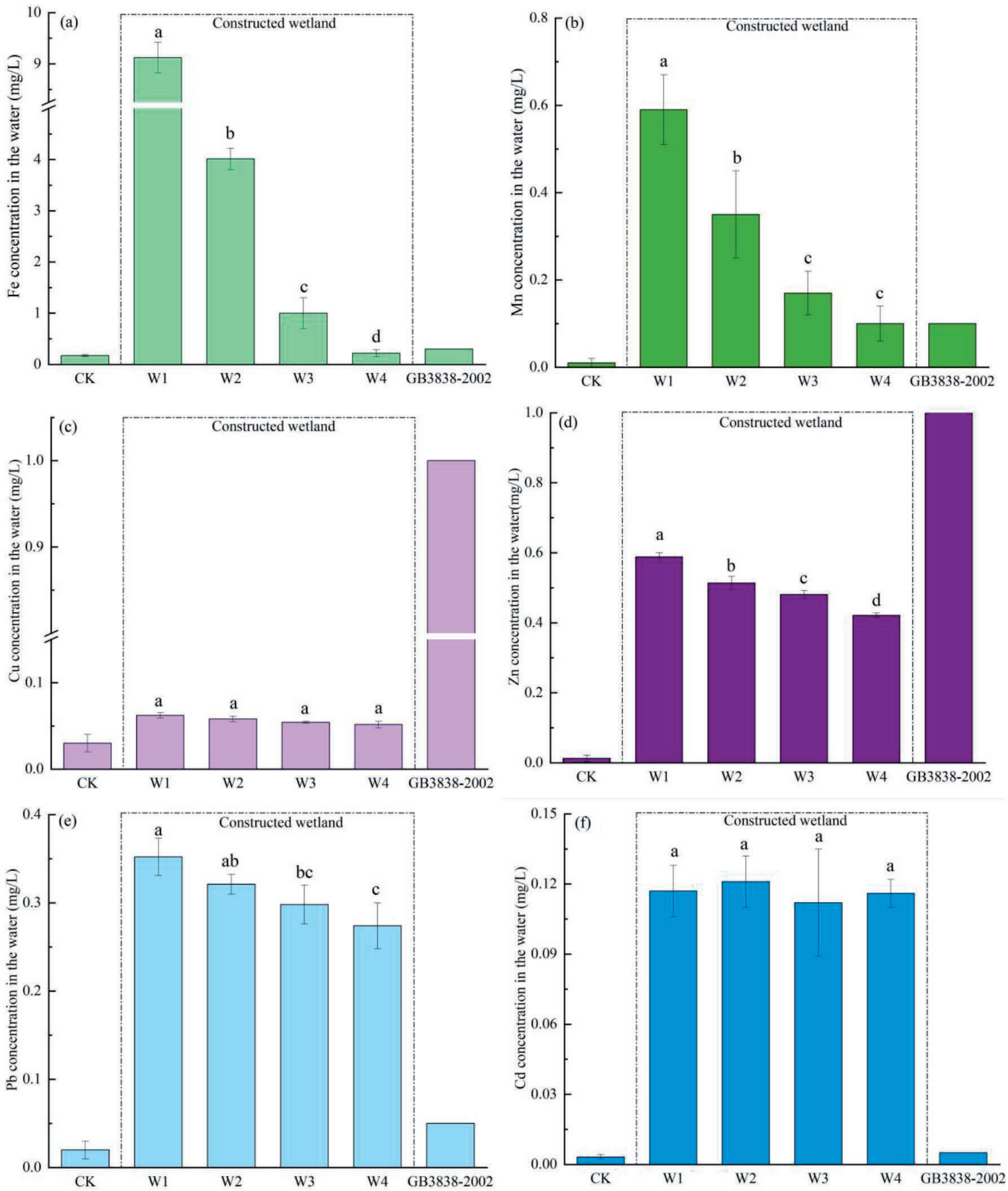

Fig. 3. Changes of contents of a) Fe, b) Mn, c) Cu, d) Zn, e) Pb, and f) Cd in the water of the wetland.

by 22.16% and 28.34%, respectively. As shown in Fig 3(d and e), the concentrations of Zn and Pb in the water were much higher than those at the CK point. Compared with the standards, the Pb concentration at the wetland outlet exceeded the standard by 5.48 times. In conclusion, the constructed wetland has a good treatment effect on Fe and Mn in AMD, but the presence of Pb and Cd in AMD can seriously impact the water quality of downstream Baihua Lake. Pb and Cd may spread through mechanisms such as bioaccumulation and sediment resuspension, affecting the aquatic ecosystem of Baihua Lake. In the short term, they may inhibit the physiological function of key species, while in the long term, they may reduce the biodiversity of Baihua Lake.

Characteristics of Heavy Metal in the Sediments of Constructed Wetlands

The adsorption of heavy metals by wetland sediments is the primary mechanism of wetland treatment for wastewater containing heavy metals. Wetland plants have well-developed aeration tissues, which are more conducive to the transport of oxygen from the aboveground parts to the plant roots, increasing the redox potential of the rhizosphere environment and

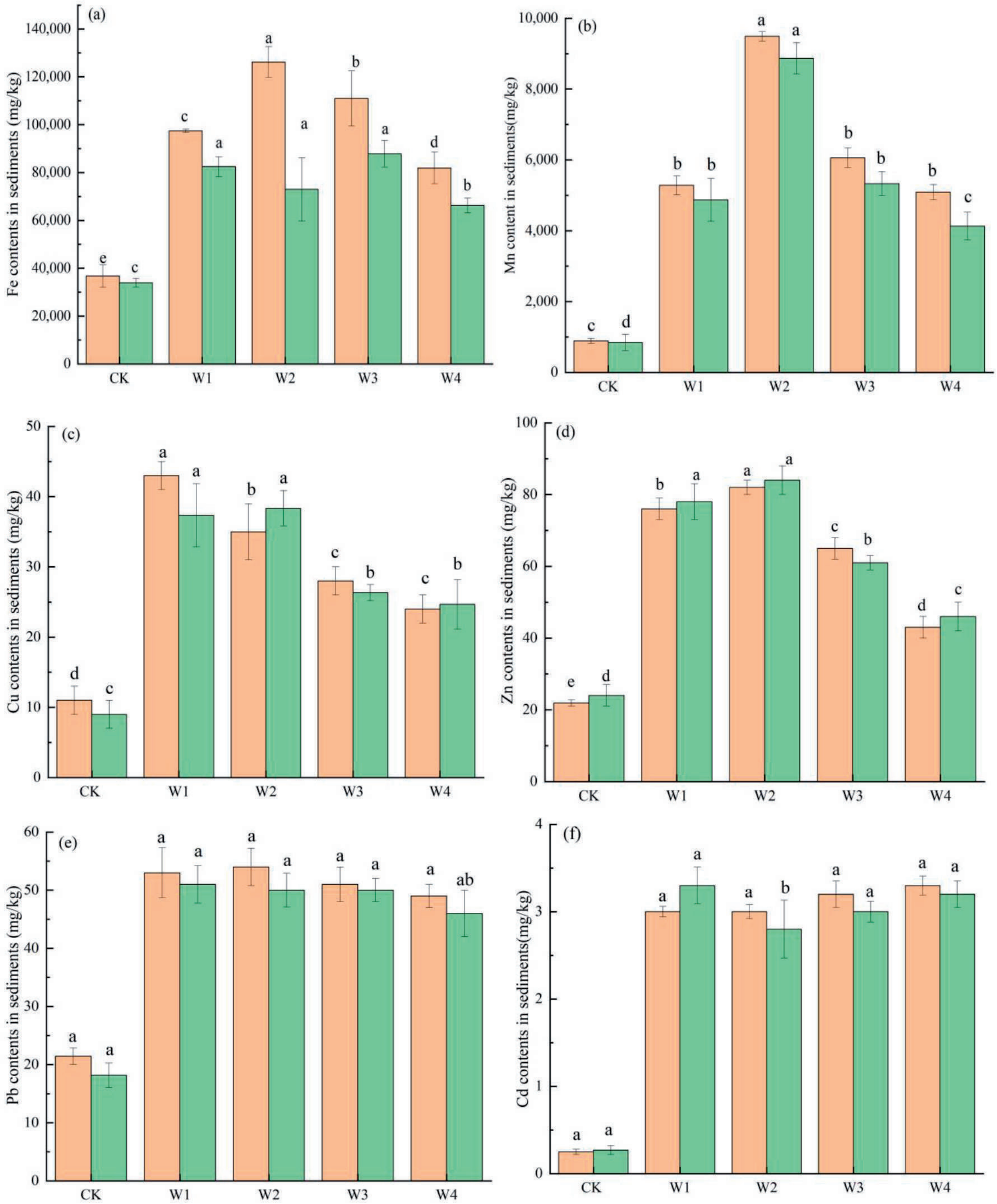

Fig. 4. Changes of contents of a) Fe, b) Mn, c) Cu, d) Zn, e) Pb, and f) Cd in the sediments of the wetland.

thereby affecting the distribution of heavy metals, such as Fe and Mn, in the wetland system. The concentrations of heavy metals in the rhizosphere and non-rhizosphere sediments at different sampling points in the wetlands are shown in Fig. 4. The order of heavy metal content in the sediments was Fe>Mn>Zn>Pb>Cu>Cd, with contents ranging from 81934 to 126216, 4130 to 9430, 43 to 83, 46 to 53, 24 to 43, and 2.8 to 3.3 mg/kg, respectively. The rhizosphere exhibited a higher Fe concentration than the non-rhizosphere, and the Fe concentration at point W2 was significantly higher than at other points ($P<0.05$). The Fe concentration in rhizosphere sediments at point W2 was 3.44 times that of the CK point and 1.73 times that of the non-rhizosphere sediments' Fe concentration, as shown in Fig. 4a). There was no significant difference in Fe concentration in sediments at other points, except for a significant decrease in Fe concentration in non-rhizosphere sediments at point W4. The Mn concentration in the sediments at the W2 sampling point was significantly higher than that at other points, and the Mn concentrations in rhizosphere and non-rhizosphere sediments at the W2 point were 10.67 and 9.98 times that of the CK point, respectively, similar to Fe. Along the flow direction, the Cu content in rhizosphere sediments was highest at the entrance of the wetland, reaching 43 mg/kg, which was 3.91 times that of the CK point, and then the Cu content in the sediments showed a decreasing trend. Zn content in the sediments showed a characteristic of first increasing and then decreasing. The Pb and Cd contents in the sediments were significantly higher than in the control points. Still, the variation in the content of Pb and Cd in the sediments among the sampling points was insignificant.

Changes in the Contents of Heavy Metals in the Plant

Fe and Mn are essential nutrients for plant growth, playing a significant role in the enzymatic reactions, photosynthesis, respiration, and nitrogen metabolism of plants [20]. In the wetlands, Fe accumulated on the surface of plants (16730-27350 mg/kg), followed by a significant accumulation of Fe in the roots of plants (2480-3310 mg/kg). The accumulation of Fe in the shoot parts of the plant was minimal (2040-2300 mg/kg). The Fe content in the root surface of the plant was highest at point W2, with a significantly higher Fe content at points W1 and W2 compared to points W3 and W4 ($P<0.05$), while the Fe content in the aboveground part of the plant was not significant. Similar to Fe, Mn is primarily accumulated on the root surface of plants (420-489 mg/kg), with a certain amount of Mn accumulation also found in the roots (320-353 mg/kg) and shoots (133-277 mg/kg). At point W4, the Mn content on the plant surface reached as high as 489 mg/kg, and the Mn content on the root surface at point W4 was significantly higher than at other points ($P<0.05$).

Cu, another essential trace element, is also involved in numerous plant physiological and biochemical reactions and is significant for photosynthesis, respiration, and antioxidant responses [21]. The concentration of Cu was primarily found on the root surfaces of plants. At the W2 sampling point, the Cu content in the root surface, roots, and shoot was notably higher than at other points ($P<0.05$). Similar to the enrichment principle of Fe, Mn, and Cu, the root surface of the plant remained the primary storage site for Zn, with the root surface accumulating 12.3-31.5 mg/kg of Zn. Additionally, there was a significant amount of Zn enrichment in the shoot of the plant (7.7-12.7 mg/kg), and the Zn content in the roots was 5.8-10.2 mg/kg. In the wetland, Pb was highly enriched in the root surface of plants (6.4-14.0 mg/kg), and Cd was concentrated on the root surface of plants, with a content of 0.79-1.00 mg/kg. There was also some Cd enrichment in the plant roots and shoots, but the content was low (Fig. 5).

Biological Enrichment and Transport Characteristics of Heavy Metals in Plants

The growth status and reproductive capacity of plants are related to the content of heavy metals in the soil. Plants thriving in environments with heavy metal stress often adopt adaptive habitat tolerance strategies to enhance their survival prospects. Consequently, these plants may develop physiological and biochemical adaptations and undergo molecular alterations to acclimate to stressors. Most plants evolve three tolerance strategies in response to heavy metal stress: accumulation, root sequestration, and avoidance [21]. The study used the W2 point of the constructed wetland as an example to study the accumulation characteristics of heavy metals in the plant. As shown in Table 1, the enrichment coefficient of *Equisetum hyemale* for Fe was 0.216, and the TF_{root} was only 0.097, indicating that Fe existed on the root surface of plants and that the ability of Fe to enter plant roots was weak. This result suggests that the tolerance strategy of *E. hyemale* toward Fe was surface accumulation.

The TF_{root} of plants for Cu was greater than 0.8, indicating a strong ability to transfer absorbed Cu from the root surface into the root interior. However, the TF_{shoot} was small, suggesting that the plant tolerance strategy for Cu was root accumulation. The BCF_{shoot} and $BCF_{surface}$ of *E. ramosissimum* for Pb, Cd, and Zn were high, and the TF_{shoot} values were all greater than 1, indicating a strong ability to transfer the absorbed Pb, Cd, and Zn from the roots to the aboveground parts. It was evident that *E. ramosissimum* adopted an enrichment strategy to tolerate Pb, Cd, and Zn. The $BCF_{surface}$, BCF_{root}, and BCF_{shoot} of plants toward Mn were small, indicating that plants adopted an avoidance strategy for Mn stress.

Discussion

Aquatic plants have well-developed aeration tissues that facilitate oxygen transport from the aboveground parts to the roots, thereby increasing the redox potential of the rhizosphere environment. This supports the aerobic respiration of the roots and allows excess oxygen to diffuse into the rhizosphere sediments via the root tips and root hairs, further elevating the redox potential and pH in this environment [22]. Additionally, during the operation of wetlands, the complexation reactions between microorganisms and organic matter consume cations in the water and release OH^- [23], which results in a higher pH at the wetland outlet than at the inlet.

Wetland treatment technology primarily relies on the synergistic interaction of sediments, plants, and microorganisms in the wetland system to precipitate Fe, Mn, and other characteristic pollutants in AMD into sediments or within plant bodies, thereby achieving the purification of AMD. The concentrations of Fe, Mn, Zn, and Pb in the water body of the wetland system have significantly decreased, with the reduction rate of Fe reaching 97.59%. This result was mainly because Fe was an important dissolved substance in AMD, and the mobility of the water body enhanced the oxygen content, causing an increase in DO in the water body (Fig. 2). The solubility of Fe(III) was low, producing Fe oxides

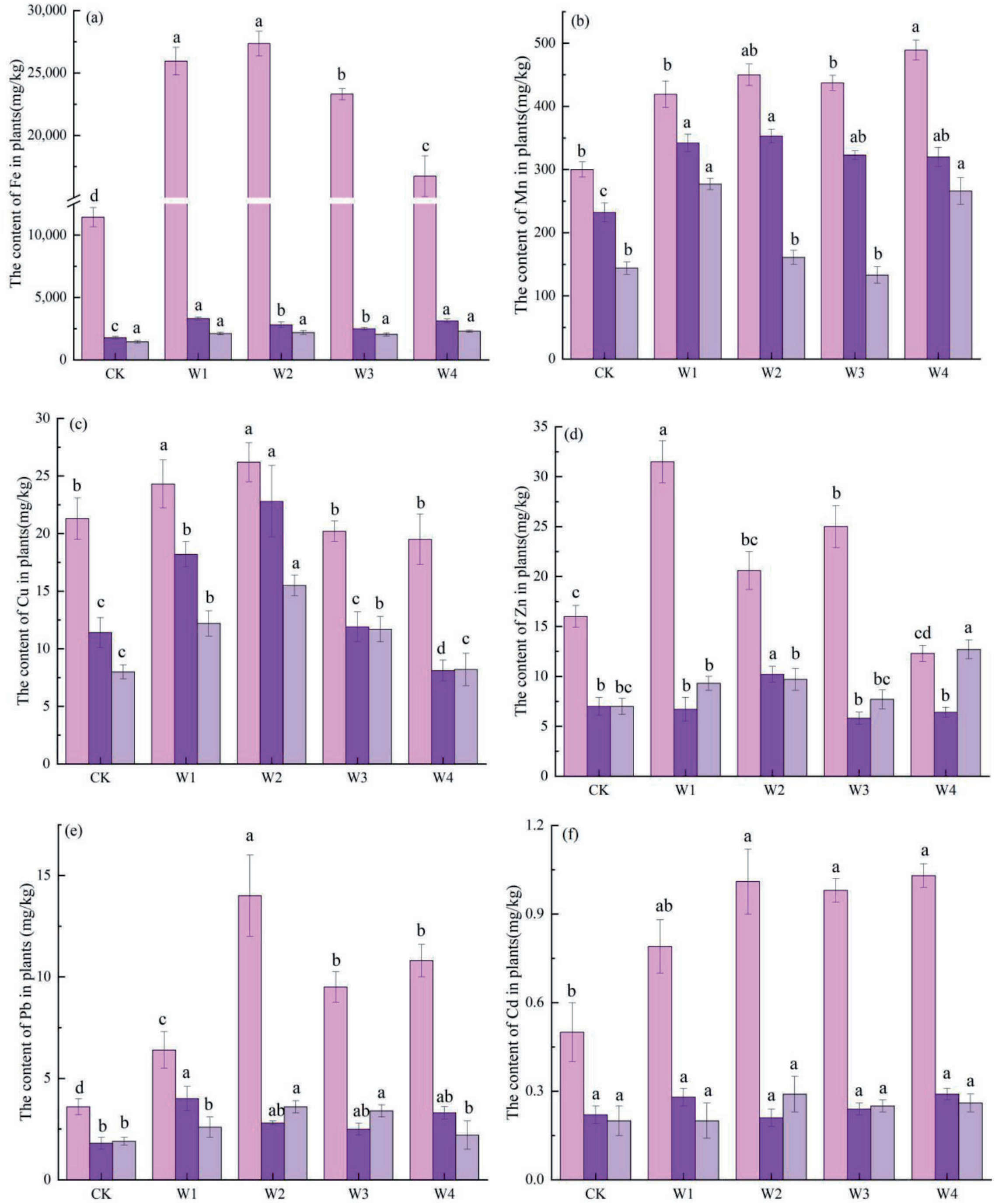

Fig. 5. Distribution characteristics of contents of a) Fe, b) Mn, c) Cu, d) Zn, e) Pb, and f) Cd in wetland plants.

Table 1. Characteristics of heavy metal accumulation and transport in *Equisetum arvense.*

Different factors	Fe	Mn	Cu	Zn	Pb	Cd
$BCF_{surface}$	0.216	0.047	0.74	0.25	0.26	0.53
BCF_{root}	0.021	0.038	0.65	0.12	0.05	0.11
BCF_{shoot}	0.017	0.018	0.30	0.12	0.17	0.15
TF_{root}	0.097	0.809	0.878	0.480	0.192	0.208
TF_{shoot}	0.810	0.474	0.462	1.000	3.400	1.364

or hydroxides precipitation [24]. Previous research by our group indicated that the rhizosphere sediments of this wetland system were composed of goethite, quartz, gypsum, and hematite [25]. Various iron minerals and other heavy metals can be effectively removed through coprecipitation. Cu, Ni, Mn, and other heavy metals can coprecipitate with iron oxides, acting as carriers to eliminate these contaminants from the water [26].

The adsorption of heavy metals by wetland sediments is the main mechanism of constructed wetlands in treating wastewater containing heavy metals. Research has indicated that the substrate exhibits the highest accumulation of heavy metals within the entire wetland ecosystem. Heavy metals entering the wetland system were filtered and retained by the substrate and then precipitated within it. This is an important way to transition heavy metals from the liquid to the solid phases in water [12].

Radial oxygen loss in aquatic plants results from natural selection in plants adapted to long-term flooding and oxygen-deficient environments. This result was achieved through the strong internal aeration tissues of aquatic plants. Plants produce oxygen through photosynthesis in their leaves and transport it to their root systems via aerenchyma tissues in the stems and roots for respiration. Aerenchyma is spongy tissue with large spaces. It provided a convenient internal pathway for gas storage and exchange within plant tissues, allowing the oxygen it transports to be diffused into the rhizosphere sediments [27]. *Equisetum ramosissimum* belongs to vascular plants and can facilitate the transport of O_2 from the aboveground parts to the roots, thereby enhancing rhizosphere Eh and forming iron-manganese oxides, called root iron plaque, covering the surface of plant roots [28]. Studies demonstrate that root iron plaque exhibits strong adsorption for divalent metal cations [29]. Root oxidation and rhizosphere Fe^{2+} concentration are two critical conditions for the formation of root iron plaque on root surfaces. Studies have shown that the addition of Fe^{2+} and Mn^{2+} significantly increases the iron and manganese content in the root iron plaque on rice seedling roots [30].

The radial oxygen loss of wetland plants increases the redox potential in the sediment, leading to an increase in the content of iron oxides in the rhizosphere sediment. Iron oxides have positively and negatively charged functional groups and a larger surface area [31], which could form stable chelates through adsorption or coprecipitation with heavy metals such as Pb and Cd. Therefore, the content of heavy metals in wetland rhizosphere sediments was higher than in non-rhizosphere sediments. In addition, due to the root oxygenation function of wetland plants, the Eh in the rhizosphere is higher than that in the non-rhizosphere [32]. The reduced Fe^{2+} in the rhizosphere is oxidized and deposited on the root surface and rhizosphere [33], resulting in a significantly higher Fe content in the rhizosphere sediments than in the non-rhizosphere.

Additionally, root exudation of oxygen creates a redox potential difference and an inverse gradient of ferrous iron concentration between the rhizosphere and the surrounding soil, providing a favorable habitat for microaerophilic iron-oxidizing bacteria. These bacteria can perform chemoautotrophic metabolism using Fe(II) as an energy source or engage in mixotrophic metabolism using organic carbon sources. They synthesize organic matter and produce a large amount of amorphous ferric hydroxide [34], the main reason for increased Fe content in rhizosphere sediments.

The absorption and accumulation of heavy metals in plants occur through three mechanisms: adsorption on the root periphery, translocation to the interior of plant roots, and subsequent transport from the roots to the aboveground parts [35]. In this study, it was observed that the heaviest metals were concentrated on the root surface. This is consistent with previous research findings. In this study, the maximum Fe, Mn, Cu, Zn, Pb, and Cd concentrations on the root surface reached 27350, 489, 26.0, 31.5, 14.0, and 1.0 mg/kg, respectively. This is due to oxygen secretion by plant roots accelerating the oxidation and hydrolysis of Fe^{2+} and Mn^{2+} in the water, leading to the formation of brownish-red Fe oxide adhering to the plant roots, forming an iron plaque ($5Fe_2O_3$ $9H_2O$) [36]. The specific surface area of iron plaque is typically greater than 200 $m^2 \cdot g^{-1}$, and its surface is rich in hydroxyl groups, which have a strong adsorption capacity for heavy metals, affecting the solid/liquid phase ion distribution in the rhizosphere soil [37]. Additionally, studies have shown that the absorption and accumulation of heavy metals by plants are positively correlated with plant growth status and root system development. Plants with larger root biomass and longer root lengths exhibit better heavy metal absorption capabilities, facilitating the distribution of microorganisms, particularly aerobic bacteria, deeper into wetland areas [38]. The root system serves as the primary organ for direct soil contact and is the most crucial site for heavy metal uptake and storage in plants. A well-developed root system indicates strong physiological activity and metabolic vigor, demonstrating enhanced capacity for nutrient absorption and oxygen secretion into the environment [39]. This makes plant roots an extremely critical factor in the purification of pollutants within constructed wetlands.

Studies have found that wetland plants can survive in harsh environments with flooding and severe heavy metal pollution. This is mainly because the iron plaque on the plant roots surface can provide a reaction matrix for the chelation and translocation of metals, such as Cu, Pb, and Zn, hindering the absorption and transport of heavy metal elements and reducing the toxicity of metal elements [40]. In addition, plant root exudates secrete a large number of metabolites that can extract heavy metals from the medium and transport them into the plant body through mineral transport channels and other means [41-43], resulting in the presence of some heavy metals in the plant roots and aboveground parts.

Conclusions

(1) Constructed wetlands can increase the pH of AMD during operation and have a good treatment effect on Fe, Mn, Cu, and Zn in AMD. The removal rates for Fe and Mn reached 97.59% and 83.05%, respectively. At the outlet of the wetland all four heavy metals at the wetland outlet meet the Class III standard of the “Surface Water Environmental Quality Standards” (GB3838-2002). However, the treatment effects of constructed wetlands on Pb and Cd in AMD were insignificant, and the discharge of Pb and Cd in AMD could have a certain impact on the water quality of downstream Baihua Lake. Therefore, future research can further explore the selection and configuration of wetland plants and the optimization of the wetland matrix to improve the removal efficiency of Pb and Cd.

(2) The content of heavy metal elements in sediments was as follows: Fe>Mn>Zn>Pb>Cu>Cd. The concentrations of heavy metals in rhizosphere sediments were higher than in non-rhizosphere sediments, with the maximum concentrations of Fe, Mn, Cu, Zn, Pb, and Cd in rhizosphere sediments being 3.44, 10.67, 3.91, 3.50, 2.52, and 12.22 times that of the control group, respectively. Under the premise of considering construction costs, it is recommended to increase the planting area of vegetation. This can not only enrich more heavy metals but also provide abundant oxygen to the rhizosphere environment, promoting the precipitation of Fe and Mn in AMD and further improving treatment efficiency.

(3) In AMD, Fe accumulated on the root surface of the plant, while Zn, Pb, and Cd had a certain degree of accumulation on the surface and within the roots of the plant. Mn has a high accumulation on the root surface, and both the root and shoot have a high accumulation amount. Therefore, when harvesting wetland plants, removing the roots as much as possible is advisable to reduce the risk of heavy metals being released back into the wetland system.

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Conflict of Interest

The authors declare no conflict of interest.

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