

Article

Remediation Techniques for Cadmium-Contaminated Dredged River Sediments after Land Disposal

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Abstract: This paper examines the remediation techniques of cadmium (Cd)-contaminated dredged river sediments after land disposal in a city in East China. Three remediation techniques, including stabilization, soil leaching, and phytoremediation, are compared by analyzing the performance of the techniques for Cd-contaminated soil remediation. The experimental results showed that the stabilization technique reduced the leaching rate of soil Cd from 33.3% to 14.3%, thus effectively reducing the biological toxicity of environmental Cd, but the total amount of Cd in soil did not decrease. Leaching soil with citric acid and oxalic acid achieved Cd removal rates of 90.1% and 92.4%, respectively. Compared with these two remediation techniques, phytoremediation was more efficient and easier to implement and had less secondary pollution, but it took more time, usually several years. In this study, these three remediation techniques were analyzed and discussed from technical, economic, and environmental safety perspectives by comprehensively considering the current status and future plans of the study site. Soil leaching was found to be the best technique for timely treatment of Cd contamination in dredged river sediments after land disposal.

Keywords: sediments; cadmium contamination; stabilization for soil remediation; soil leaching; phytoremediation



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1. Introduction

With recent social and economic developments, an increasing amount of industrial, agricultural, and domestic sewage waste has been regularly discharged into urban rivers, causing continuous river deterioration [1]. Dredging is an effective treatment method for urban rivers with fetid and dark-colored water. Dredged river sediments usually require further treatment, such as ex situ land or landfill disposal. The heavy metal Cd is one of the most common contaminants in river sediments [2–4]. Cadmium has high mobility in soil and is highly toxic [5–9]. Even at low concentrations, this contaminant can affect the composition and structure of plant enzymes, thereby slowing plant growth and development, can accumulate in plants, and can even cause plants to be carcinogenic [10–12]. For most crops, Cd can also inhibit normal development, leading to substantial crop yield reduction [13]. When Cd enters the human body through the food chain, it accumulates in the kidney and liver, leading to many problems, such as renal dysfunction, lung cancer, and neurological and reproductive diseases [14–17]. In addition, Cd can also alter the community structure and active biomass of soil microbes, thereby affecting the bioaccessibility and release of nutrients in soil [18–22].

There are two main ideas to remediate Cd-contaminated soil: (1) changing the form of Cd in soil to reduce its mobility and bioavailability, and (2) reducing the Cd concentrations in soil by removing Cd from the soil. The remediation approaches can be divided into two

categories: (1) physical and chemical methods, such as stabilization remediation technology [23–25], soil leaching [26–28], soil exchange method, electric remediation method [29] and thermal desorption technology [30]; (2) biological methods, such as microbial remediation [31], phytoremediation [32–35], and animal remediation [36]. Although single remediation methods have their own advantages, they often have specific limitations. Therefore, combined remediation technology is also commonly used in the application of soil remediation [37].

Stabilization, soil leaching, and phytoremediation are the most widely used remediation approaches in practical engineering. Stabilization for soil remediation refers to effectively reducing the bioavailability and mobility of Cd in soil with passivators, modifiers, surfactants, and other reagents or materials that react with Cd through complexation, precipitation, adsorption, etc. Soil leaching refers to the removal of Cd from soil by transferring Cd from contaminated soil into a leached solution through the addition of chemical eluents that increase the solubility of Cd in soil via precipitation, adsorption, chelation, etc. Phytoremediation is a decontamination process mediated by the plants, involving various steps including heavy-metal uptake (phytoextraction), accumulation and translocation of heavy metals (phytoaccumulation), their stabilization in the root zone (phytostabilization), and emission to atmosphere (phytovolatilization) [38]. Phytoextraction refers to contaminants are absorbed by the plants along with nutrients and water. The contaminants are then precipitated and accumulated in the shoot or leaves of the plant by the process called phytoaccumulation. Phytostabilization can achieve in-situ immobilization or inactivation of contaminants by absorbing them on the roots of plants [39]. Phytovolatilization refers to plants transport contaminant into the xylem that can further transformed into volatile forms, and finally released in the atmosphere by stomata.

Previous studies have focused on the remediation of Cd contamination in terrestrial soils. However, there are few studies on the remediation of Cd contaminant in river sediments. It is of great significance to select an appropriate remediation method for Cd-contaminated river sediment for improving remediation efficiency and reducing economic cost. A dredged sediment disposal site was used as an example in this paper to investigate the remediation of Cd-contaminated river sediments. The feasibility and applicability of stabilization, soil leaching, and phytoremediation were comparatively analyzed in detail. The results of this study provide a theoretical and reference basis for the further application and development of remediation techniques for Cd-contaminated soil.

2. Materials and Methods

2.1. Basic Description of the Studied Site

The dredged sediment disposal site was located at the urban-rural boundary area, where farmlands and rivers comprise most of the area, with fewer sensitive sites and low population density. The disposal site was mostly wasteland covered with weeds. The layer of dredged river sediments on the disposal site had an average depth of approximately 2.0 m and a volume of approximately 8000 m³. The latest land use plan designates the disposal site as agricultural land. If the dredged river sediments are not decontaminated in a timely manner, the current soil quality might not meet the functional requirements for subsequent agricultural land use, thereby causing environmental pollution incidents. Before dredging, river sediments which consist mainly of fine sand and clay were sampled and measured by inductively coupled plasma atomic emission spectrometry, and the results are shown in Table 1. The pH was measured in suspension of soil and water. The study results showed that only the Cd concentration exceeded the risk screening value.

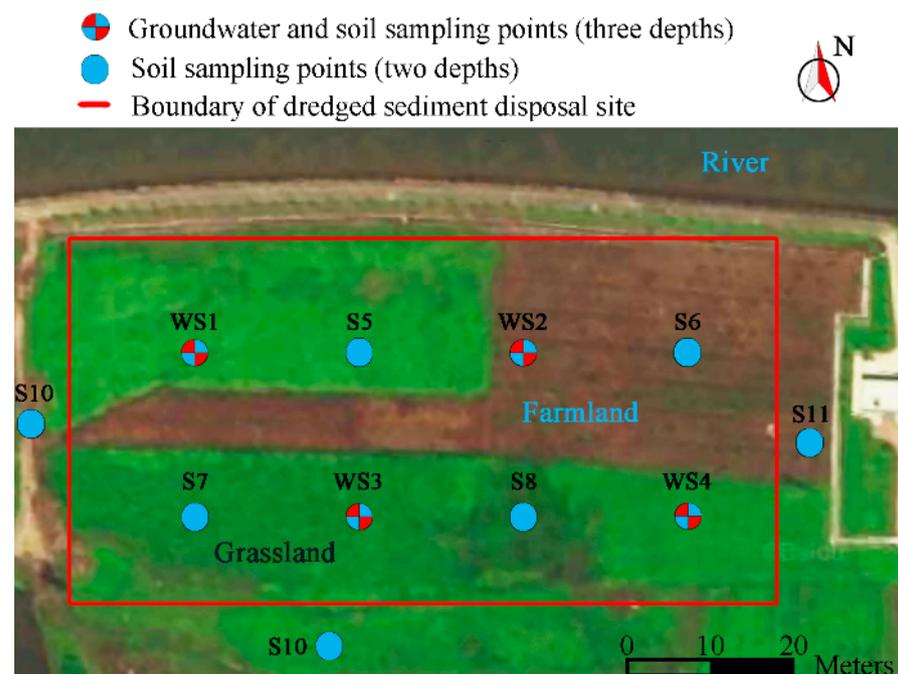
Table 1. Heavy metal concentrations (mg/kg) in dredged sediment samples.

Qualities Tested	Risk Screening Value				Test Results	Standard
	<5.5	5.5~6.5	6.5~7.5	>7.5		
pH	<5.5	5.5~6.5	6.5~7.5	>7.5	7.75~8.66	
Cd	0.3	0.3	0.3	0.6	1.26	above
Cu	50	50	100	100	59.48	under
Pb	70	90	120	170	66.96	under
Zn	200	200	250	300	238.95	under
Hg	1.3	1.8	2.4	3.4	1.31	under

Note: The standards reference “Soil Environment Quality—Risk control standard for soil contamination of agriculture land” (GB 15618-2018).

2.2. Sampling and Pretreatment

According to the detection results of Cd-contaminated river sediments, a further pollution survey and risk assessment of the disposal site were carried out. The results of the survey and drilling indicated that the dredged sediments were piled in a cuboid shape, with a thickness of approximately 2.0 m, as shown in Figure 1. To determine whether the native soil under the sediment layer was contaminated, stratified sampling at two or three depths was performed at each monitoring site. The depth of deep soil sampling points is more than the thickness of dredged sediments. Meanwhile, four underground water monitoring wells were constructed at each monitoring site to collect groundwater samples for ascertaining whether the soil underlying the sediments was contaminated. In addition, soil sampling sites with two layers were established within 10 m of the east, south, and west boundaries of the disposal site (a river was on the north side of the disposal site) to determine whether the soil surrounding the disposal site was contaminated by dredged sediments. A total of 26 soil samples and four groundwater samples were collected from 11 soil sampling sites and four groundwater sampling sites inside and outside of the study site. The layout of the disposal site and sampling sites is shown in Figure 1.

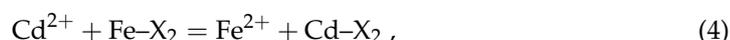
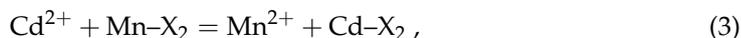
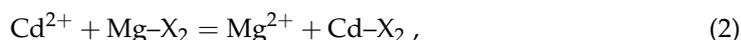
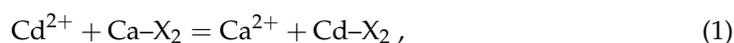
**Figure 1.** Distribution of soil and groundwater sampling points.

After removing stones in the soil, the soil samples were reduced to 100 g by quartering method. The soil samples were grinded and pressed with wooden sticks after air drying,

and then was screened by 2 mm nylon screen. After evenly mixing the soil samples, grind them with an agate mortar. After passing the 100 mesh nylon screen, it is left to be tested. Groundwater samples were collected in polyethylene plastic bottles. Add nitric acid to the water sample for acidification (pH between 1 and 2) and leave it to be tested.

2.3. Stabilization for Remediation

Stabilization for remediation refers to the use of physical and chemical methods that convert contaminants into insoluble, low-mobility, or low-toxicity forms. The key to successful stabilization for remediation is selecting an appropriate stabilizer. We choose a green and efficient stabilizing material with a pH value of about 7.5, the particle size is less than 1 mm, the density is 1.2~1.5 g/cm³, the moisture content is 3~5%. The appearance of the stabilizing material is light brown powder, which is mainly made of natural mineral crystals of zeolite, mixed with a small amount of calcium and magnesium compounds, iron and manganese salts and clay. Zeolite has a large specific surface area and strong electrostatic field, which performs significant ion exchange capacity and adsorption characteristics [40]. Mineral crystals have excess negative charge, and the crystal structure can facilitate the adsorption of Cd ions in contaminated soil and exchange with compensating cations (Ca²⁺, Mg²⁺, Mn²⁺ and Fe²⁺) to form more stable compounds. According to Appelo and Postma [41], the order of adsorption affinity of divalent cations is: Cd²⁺ > Ca²⁺ > Mg²⁺ > Mn²⁺ > Fe²⁺. This means that Cd²⁺ has a stronger adsorption affinity than Ca²⁺, Mg²⁺, Mn²⁺ and Fe²⁺, thus converting Cd into a less soluble form through cation exchange, as shown in Figure 2. The related ion exchange reaction equations are shown below:



where ()-X₂ denotes the cation exchanger or an exchange position. Stabilizing material can reduce the chemical effectiveness of pollutants, weaken their migration and diffusion ability, and thus achieve the purpose of preventing their transformation and endangering human health. The stabilized material has the following main characteristics: (a) the cation exchange capacity is up to 140 meq/100 g, (b) no biological toxicity, (c) low cost and quick results.

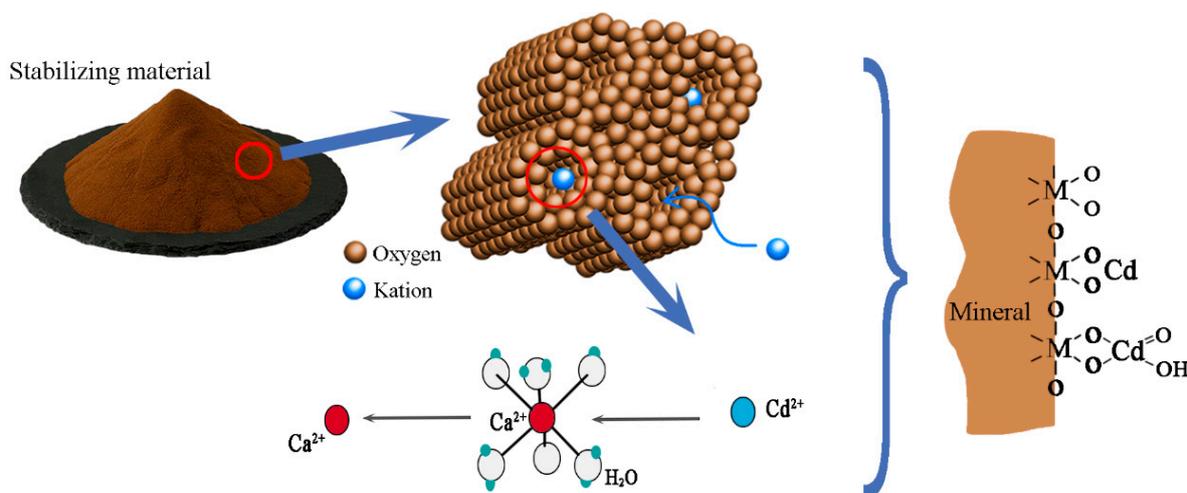


Figure 2. Transformation mechanisms of stabilization materials.

The dose-dependence of the stabilizing effect of stabilizing material on the soil Cd concentration was experimentally investigated. The detection index was the leaching rate of Cd from stabilized soil samples. Soil samples were collected from site and were dried and passed through a 2-mm sieve. A total of ten samples (200 g each) were accurately weighed and placed in ten 1000-mL beakers. Stabilizing materials were added at mass fractions of 0, 2.0%, 2.5%, 3.0%, 3.5%, 4.0%, 4.5%, 5.0%, 5.5%, and 6.0%, respectively. Deionized water was added to each sample at a solid-to-liquid ratio of 1:0.5, mixed well, sealed, and aged at room temperature (15 °C) for seven days. Samples were then dried and subjected to leaching and detection. The above experiment was repeated three times to ensure the reliability of the results.

2.4. Soil Leaching

Soil leaching removes Cd from soil by adding chemical eluents to contaminated soil through desorption, chelation, dissolution, etc. This method typically involves three steps: mixing the eluent with soil, collecting the leached solution, and treating and recovering the leached solution [42]. Commonly used eluents mainly include inorganic solvents, chelating agents, and surfactants.

The present study investigated the influences of eluent type and the eluent-to-soil ratio on Cd leaching from soil. The effectiveness of leaching was evaluated with the Cd concentrations detected in the soil samples after leaching. The eluents used in this study included (1) deionized water, (2) 0.1 mol/L hydrochloric acid (HCl), (3) 0.1 mol/L sulfuric acid (H₂SO₄), (4) 0.1 mol/L HCl + 0.4 mol/L ferric chloride (FeCl₃), (5) 1.0 mol/L citric acid (C₆H₈O₇), and (6) 1.0 mol/L oxalic acid (H₂C₂O₄). Three control experiments were designed for each eluent. The related ion exchange reaction equations are shown below:



3. Result

3.1. Determination of Cd

The concentration of Cd in soil and groundwater was determined by referring to the “Soil quality–Determination of lead, cadmium–Graphite furnace atomic absorption spectrophotometry” (GB/T 17141-1997) and “Water quality–Determination of copper, zinc, lead and cadmium–Atomic absorption spectrometry” (GB 7475-87) in China. Cd concentration in 26 soil samples was detected three times by AAS9000 atomic absorption spectrometer. The results were compared with the corresponding standard limits, as shown in Figure 3. Risk screening value (0.3 mg/kg) and risk control value (4.0 mg/kg) refer to the “Soil Environment Quality—Risk control standard for soil contamination of agriculture land” (GB 15618-2018) in China. Figure 3 shows that the Cd in disposal site mainly exists in the river sediment and does not spread to the surrounding area (S9 and S11 are lower than the risk screening value). The pH value of the sediments at the disposal site ranged from 7.20–7.95. Cd was detected in all river sediment samples. The Cd concentrations in 12 soil samples were 0.5 to 7.0 times the risk screening value, with an over-limit ratio of 60%. The Cd concentrations in two samples (WS3-1 and S6-1) exceeded the risk control value. The pH values of soil samples outside the disposal site ranged from 7.16 to 7.91, with no Cd concentrations exceeding the risk screening value. In addition, the pH values of the four groundwater samples ranged from 7.20 to 7.29, with Cd detected in one of the samples at a concentration lower than the Class III limit of the “standard for groundwater quality” (GB/T14848-2017) in China, that is, the groundwater of the disposal site was not polluted.

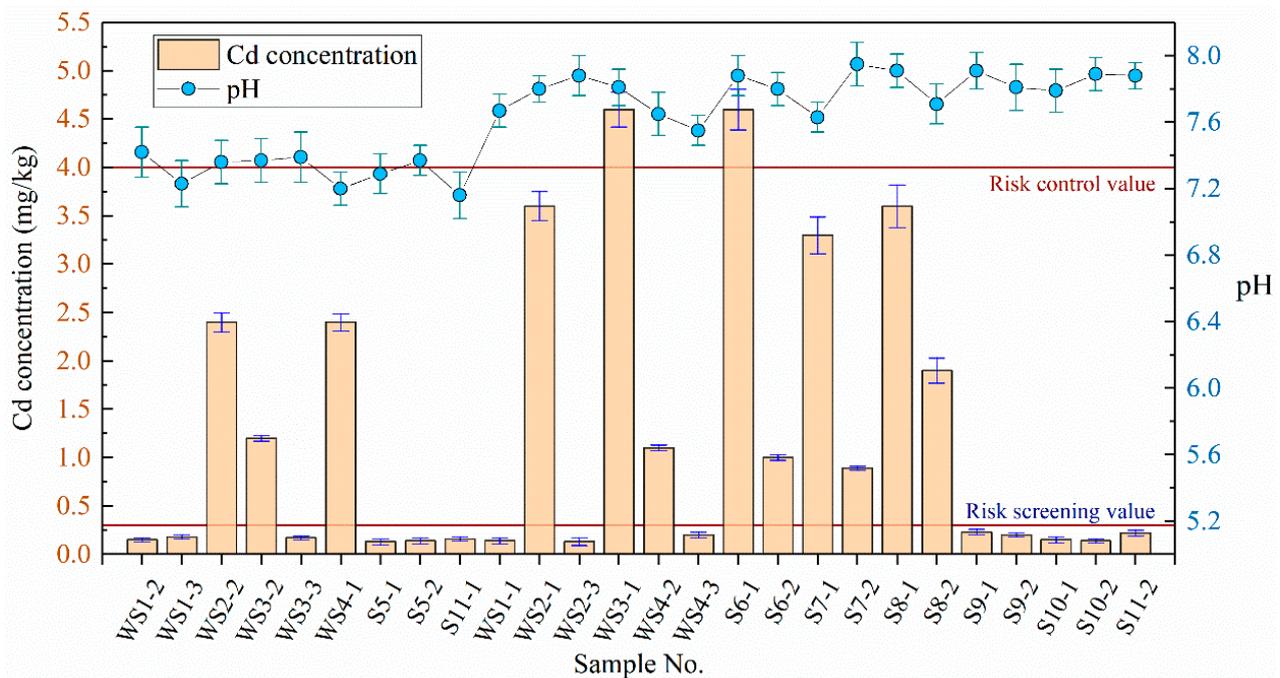


Figure 3. Detection results of Cd and pH in soil samples.

3.2. Stabilization for Remediation

Soil sample WS3-1 (the Cd concentration in the sample exceeded the risk control value) was selected to investigate the dose-dependence of stabilizing effect of stabilizing material on the soil Cd concentration. The detection results are shown in Figure 4.

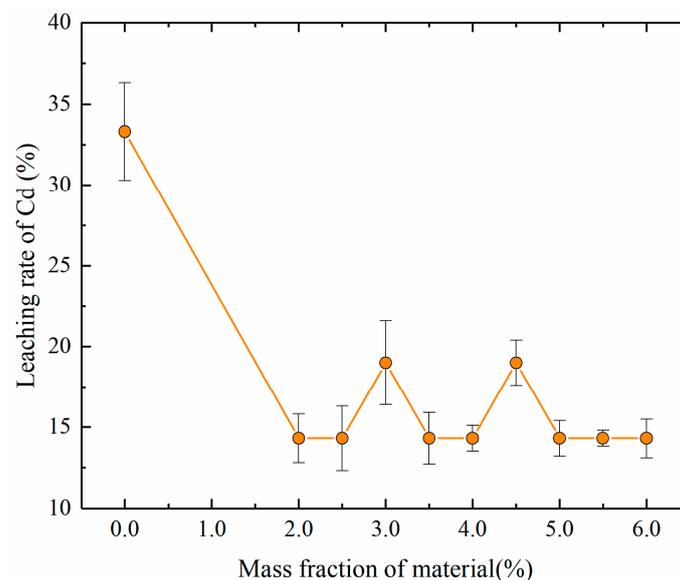


Figure 4. Dependence of the leaching rate of Cd on the mass fractions of stabilizing material.

The leaching rate of Cd decreased from 33.3% to 14.3% as the mass fraction of stabilizing material increased from 0 to 2%, and further increases of the mass fraction of stabilizing material did not significantly affect the leaching rate of Cd. The results indicate that although stabilizing material can stabilize Cd, it did not significantly affect the leaching rate of Cd within the scope of this study. This finding may have occurred because the rich soluble organic matter in soil samples from river sediments binds to Cd and precipi-

tates together during the leaching process. This result also indicates that stabilization for remediation can significantly reduce the toxicity of Cd-contaminated soil.

3.3. Soil Leaching

Experimental results of soil leaching showed that the leaching effect of deionized water on Cd was the worst, followed by the inorganic eluents HCl and H₂SO₄, while the mixed inorganic eluent HCl + FeCl₃ and the organic eluents, citric acid and oxalic acid, had good leaching effects of Cd in the soil, with the highest removal rates of 73.3%, 90.1%, and 92.4%, respectively (Figure 5).

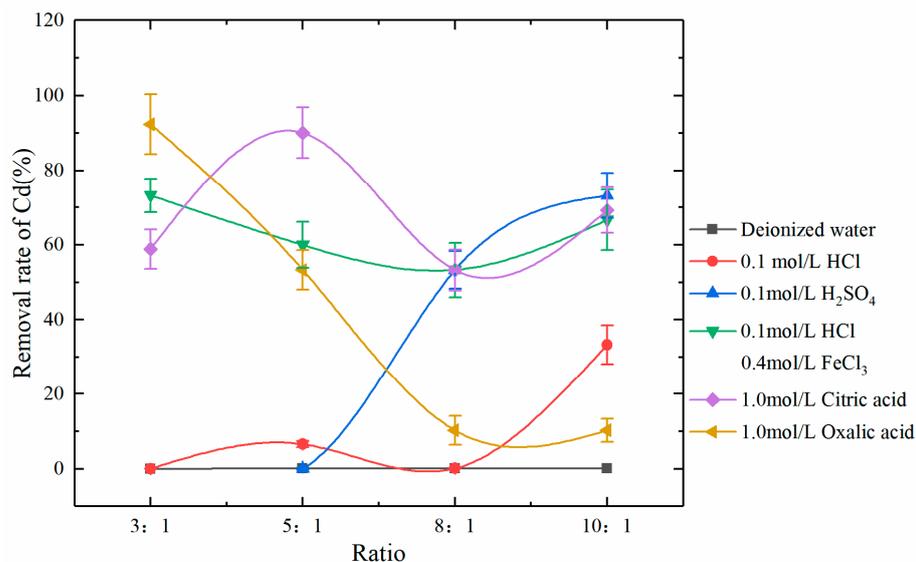


Figure 5. Removal rates of Cd by various eluents at different eluent-to-soil ratios.

After leaching with deionized water, there was almost no removal of Cd, indicating that there was very little water-soluble Cd in the soil samples. Theoretically, all three types of inorganic eluents can provide H⁺ to replace carbonate-bound Cd in soil samples so that Cd can be dissolved into water. However, the ability of H⁺ to replace Cd is weak [43], resulting in the poor leaching effect of Cd by the eluents HCl and H₂SO₄ that mainly rely on H⁺. The mixed eluent HCl + FeCl₃ not only provides H⁺ and Fe³⁺ to replace Cd in soil but also provides a large amount of H⁺ due to hydrolysis of Fe³⁺ during leaching. In addition, the excellent complexation ability of highly soluble Cl⁻ for Cd can significantly increase the extraction of Cd from soil [44,45]. It is worth noting that the removal capacity of the mixed eluent for Cd did not increase with the eluent-to-soil ratio, because H⁺ only had a significant removal effect on the carbonate-bound Cd. The excess H⁺ would lose its value when the carbonate-bound Cd was removed. Unlike inorganic eluents, which are more targeted on removing carbonate-bound Cd, the organic eluents, citric acid, and oxalic acid can also chelate exchangeable Cd and thus enhance the removal of exchangeable Cd in soil. In this study, the leaching effects of citric acid and oxalic acid on Cd were superior to those of inorganic acids, which may be due to the large proportion of exchangeable Cd. The deprotonated -OH group and -COOH group formed coordination compounds with exchangeable Cd ions, which improved their mobility in the soil and significantly increased the leaching rate of Cd [46,47]. In addition, the results showed that the removal rate of citric acid and oxalic acid on Cd be restricted by the eluent-to-soil ratio. The optimal ratio was 3:1 and 5:1 respectively in the research range. Thus, the removal rate of Cd can be significantly improved through optimization measures, such as choosing a proper eluent-to-soil ratio, performing leaching multiple times, and prolonging the leaching duration.

3.4. Phytoremediation

Phytoremediation is an in situ remediation technique mainly using hyperaccumulators to absorb heavy metal ions. Heavy metal ions are retained and accumulate in plants through complexation and localization by glutathione, phytochelatins, metallothioneins, and organic acids in the plants, thereby reducing the toxicity of and environmental pollution caused by heavy metals [48]. Due to the variety of hyperaccumulators and long growth cycle, it is usually difficult to carry out relevant experiments in soil remediation. Previous studies usually have excellent reference significance. The known Cd hyperaccumulators and corresponding study cases are shown in Table 2.

Table 2. Cd hyperaccumulators and application cases.

Plant	Background Value	Cd Concentration in Plants (mg/kg)	Reference
<i>Festuca arundinacea</i>	2.8 mg/kg	49.0–64.0	[49]
<i>Celosia argentea</i>	4.2 mg/kg	101.0–105.0	[50]
<i>Bidens pilosa</i>	4.4 mg/kg	122.0–138.0	[51]
<i>Solanum nigrum</i>	12.0 mg/kg	84.82–92.94	[52]
<i>Trifolium repens</i>	25.5 mg/kg	56.0–68.0	[53]
<i>Mirabilis jalapa</i>	30.0 mg/kg	63.93–77.41	[54]
<i>Brassica napus</i>	50.0 mg/kg	371.1–409.7	[55]
<i>Indian mustard</i>	75.0 mg/kg	420.0–480.0	[56]
<i>Sedum plumbizincicola</i>	210.0 mg/kg	1400.0–1847.7	[57]
<i>Viola inconspicua</i>	25.0 $\mu\text{mol/L}$	760.0–800.0	[58]
<i>Viola baoshanensis</i>	25.0 $\mu\text{mol/L}$	975.0–995.0	[58]
<i>Ricinus communis</i>	27.3 $\mu\text{mol/L}$	1700.0–1830.0	[59]
<i>Sedum alfredii</i>	50.0 $\mu\text{mol/L}$	5500.0–5800.0	[60]
<i>Salix aureo-pendula</i>	107 $\mu\text{mol/L}$	97.0–110.0	[61]
<i>Phytolacca acinosa</i>	273 $\mu\text{mol/L}$	320.0–500.0	[62]

It is worth noting that the common unit of Cd background value is mg/kg or $\mu\text{mol/L}$ due to different experimental conditions. The former is usually used to characterize background value in contaminated soil, while the latter is mostly used in artificially prepared solutions in the laboratory. Previous studies have shown that both plant species and Cd concentration in the soil have an impact on the remediation effect. The efficiency of various hyperaccumulators is different under the same concentration, for example, *Viola inconspicua* and *Viola baoshanensis*. Furthermore, the background value of contaminants in soil has a significant effect on the accumulation efficiency of plants. Li et al. (2020) found that the remediation ability of the hyperaccumulator was inhibited when the Cd concentration in the soil was too high [50]. As shown in Table 2, *Festuca arundinacea*, *Celosia argentea*, and *Bidens pilosa* have relatively significant effects in the remediation of contaminated soil with low Cd concentration, while *Brassica napus*, *Indian mustard*, and *Sedum plumbizincicola* are often used in the remediation of contaminated soil with high Cd concentration. Although *Viola baoshanensis*, *Viola inconspicua*, and *Ricinus communis* also show outstanding accumulation capacity for Cd, they have not been widely used due to the limitations of survival rate, soil environment, and climate conditions. In general, phytoremediation is low cost, efficient, simple, effective, and pollution free. However, this technique has some limitations: (1) the slow growth rate of plants can significantly extend the remediation time to several years. (2) Many phytoremediation studies are still in the experimental stage, with few known plant species that only possess tolerance to single factors. Enhancing phytoremediation

ability and resource utilization after phytoremediation are feasible ways to improve the practical application of phytoremediation [63,64].

Considering that various hyperaccumulators have different application ranges of Cd concentration, *Festuca arundinacea* that is most similar to that of the disposal site (Figure 3) is an appropriate choice for the remediation of the study site. Qin et al. (2021) conducted a series of experiments to investigate the impact of planting density on the phytoremediation efficiency of *Festuca arundinacea* in Cd-contaminated soil [49], they founded that *Festuca arundinacea* can remove 1.78–2.66 g Cd/m³ from the soil at a planting density of 1.0–1.4 kg/m², if the whole plant was harvested at the end of the treatment. Assuming that the remediation efficiency of Qin et al. (2021) is also applicable to the disposal site, in first growth cycle, the Cd remove rate is 23.9~36.0% in areas exceeding the risk control value, and 48.6~72.7% in areas exceeding the risk screening value. Cd removal rate can be further improved by repeated planting of *Festuca arundinacea*, but it significantly increases the duration of remediation.

4. Discussion

According to the experimental results of the three remediation techniques and related case studies, all three remediation techniques can remove Cd from soil samples collected at the study site. Under the premise that the remediation effect meets the standards, three remediation techniques were compared in this paper from various aspects, and the evaluation indexes of each remediation technique are shown in Table 3.

Table 3. Comparative analysis of three remediation techniques.

Evaluation Index	Stabilization	Leaching	Phytoremediation
Applicability	Applicable to soils contaminated with multiple heavy metals	Applicable to soils contaminated with multiple heavy metals	Applicable to soils contaminated with single heavy metals
Effectiveness	The leaching rate of Cd is 14.3%, but the total amount of Cd cannot be reduced	The Cd removal rate is up to 92.4%	The estimated Cd removal rate is 23.9~36.0% in areas exceeding the risk control value in first growth cycle, which can be improved by repeating planting
Controlling factor	Stabilizing material type and mass fraction of stabilizing material	Eluent type and eluent-to-soil ratios	Plant species, planting density, climate and soil type, etc.
Remediation time	5–7 months	2–4 months	20–60 months
Remediation cost	Cost of stabilizing material: 50~200 yuan per ton of soil remediation	Cost of eluent: 500~800 yuan per ton of soil remediation [65]	Plant cost: 3500~65,000 yuan per hectare; Human cost: 25,000~50,000 yuan per hectare [66]
Estimated cost-effectiveness ^ψ	80,000 yuan	55,000 yuan	5000 yuan ^λ
Nutrient loss	No loss of nutrients	Large nutrient loss	No loss of nutrients
Secondary pollution	Hardly causes secondary pollution	Improper disposal of the leached solution can easily cause secondary pollution	The burning of plants may cause secondary pollution

^ψ: Cost-effective denotes the cost of removing or stabilizing 1% of Cd, ^λ: This is only for the first phytoremediation cycle, and the cost-effectiveness will increase in subsequent cycles.

As shown in Table 3, stabilization technology and leaching technology both can be used for remediation of various heavy metal contaminated soils, while phytoremediation is often suitable for contaminated soil with single heavy metal due to the single tolerance characteristics of most hyperaccumulators. The stabilization technology reduced the leaching rate of Cd from 33.3% to 14.3%, which is inferior to the soil leaching technology

with Cd removal rate of 92.4%. The effectiveness of phytoremediation can be continuously improved through repeated planting of hyperaccumulator. Take *Festuca arundinacea* as an example, the estimated Cd removal rate is about 30% in areas exceeding the risk control value in first growth cycle. Previous studies have shown that the Cd removal rates of more than 80% can be expected with sufficient remediation cycles [49]. It is worth noting that the effectiveness of a single remediation cycle (a growth cycle of hyperaccumulator) usually decrease continuously as the concentration of Cd in the soil decreases with the process of phytoremediation. Moreover, phytoremediation has greater uncertainty in terms of the control factors of remediation effectiveness, so it is necessary to select plants according to local conditions [60,66]. The remediation time of phytoremediation is about seven times that of stabilization technology and 13 times that of leaching technology, which means that phytoremediation is not suitable for emergency remediation. The cost of removing or stabilizing 1% of Cd was estimated to compare the cost-effectiveness of the three methods. Phytoremediation is the best cost-effectiveness, followed by soil leaching and stabilization. In other words, Phytoremediation will be the first choice when remediation time is sufficient. Nutrient loss is a highly concerned evaluation index for contaminated sites planned for agricultural used in the future. Stabilization and phytoremediation can usually preserve native soil nutrients, while soil leaching will cause considerable nutrient loss. However, some scholars believe that soil nutrients can be effectively replenished by introducing microbial community and building level ditches or rills, and thus nutrient loss is not a particularly serious problem [67–69]. In addition, with the development and improvement of technology, the probability of secondary pollution caused by the three remediation methods is relatively low.

5. Conclusions

The selection of remediation method requires comprehensive consideration of technology effectiveness, economy and environment safety. In the remediation engineering of the river sediment disposal sites, both stabilization and soil leaching meet the timeliness requirements of the remediation project. It is worth noting that since the city plans to use the study site as agricultural land, the reference standard mainly requires the maximum total Cd concentration. Therefore, stabilization for remediation cannot meet the remediation target. Soil leaching is the better choice, with an estimated remediation efficiency of about 90%. Phytoremediation can be used as an auxiliary means of remediation under the condition of sufficient remediation time. According to the degree of pollution, this site can be divided into two regions, a region with an over-limit risk control value and a region with an over-limit risk screening value but below-limit risk control value. Soil leaching can be adopted for the former region, and phytoremediation can be adopted for the latter area. This divided-region approach can maintain the remediation efficiency at 80%–90% and reduce the economic cost by 74%.

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