Research Article

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Effect of different ramie (Boehmeria nivea L. Gaud) cultivars on the adsorption of heavy metal ions cadmium and lead in the remediation of contaminated farmland soils

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Abstract: Heavy metal ions, including cadmium (Cd) and lead (Pb), are serious pollutants in farmland soils. The effective removal of heavy metals is an important task in soil remediation. This study aimed to evaluate the ability of seven ramie (Boehmeria nivea L. Gaud) cultivars to remove heavy metals. Results showed that the seven ramie varieties grew well in Cd and Pb polluted soils. The aboveground biological tissues and raw fiber yield of “Zhongzhui” were 20.71 and 24.61 Mg ha⁻¹ per year, respectively, which were significantly higher than those of the six other varieties. Cd levels in each ramie part can be arranged as husks > root > stem bone > leaf > raw fiber, while Pb levels in each ramie part can be arranged as root > leaf > husks > stem bone > raw fiber. The Cd content in the shoots of “Zhongzhui” was 19.89 mg kg⁻¹, and the Pb content of the aboveground shoots of “Shiqianzhugenma” was 9.41 mg kg⁻¹. The extraction efficiency of Cd in “Zhongzhui” was greatly higher than those of the six other varieties. The extraction efficiency of Pb was similar in all varieties. Our observations suggest that ramie can be used to remove toxic ions (Cd and Pb). This study provides a new understanding of planting ramie for heavy metal removal from contaminated soils.

Keywords: Boehmeria nivea, cadmium, lead, phytoremediation, soil pollution

1 Introduction

Soil pollution related to heavy chemical metals rapidly increased in the environment worldwide in the past few decades [1]. The long-term mining of mineral resources has polluted large areas of soil and water with heavy metals, such as cadmium (Cd) and lead (Pb). These heavy metals cause losses of yield and quality of agricultural products and can be absorbed by plants and further enter the food chain, causing human health risks [2,3]. Large areas that have been contaminated with heavy metals should be effectively treated. Many valuable works have focused on the removal of heavy metal ions from soils or wastewaters [4,5].

Phytoremediation is a feasible method to clean up contaminated soils because it is sustainable, inexpensive, and environmentally safe. Much research on heavy metal phytoremediation has focused on identifying hyperaccumulating plants [6,7]. McGrath et al. [8] conducted a three-year field experiment (1998–2000) in Bedfordshire (England) and found that there mediation efficiency of Cd and zinc (Zn) can reach 21.7 and 4.4%, respectively. Hyperaccumulative plants have strong resistance and tolerance to heavy metals with high translocation coefficient. However, most of them are herbaceous and not fit to be used in phytoremediation because of their inherent limitations, such as small biomass, slow growth, shallow root system, soil regionality, and difficulties in mechanized operations [9]. Recent studies have increasingly focused on cash crops, such as sunflower, corn, and flax [10,11], which are characterized by fast growth, high biomass, strong tolerance of heavy metals, and ease of management. The application of ethylene diamine tetraacetic
acid in sunflower plants can tolerate or accumulate a considerable amount of Pb, which can be used for the remediation of Pb pollution soil [10]. The research on the Cd transport and accumulation characteristics of 19 corn cultivars found two corn varieties with potential for phytoremediation and can be used to remediate mildly or moderately Cd-contaminated soil [11,12]. When planting flax, corn, and sunflower under treatment with the same concentration of Cd, the Cd content in the stalk of flax is 3–5 times higher than that of corn and sunflower, while the capabilities of flax roots to absorb and transfer Cd$^{2+}$ ions are strong [13]. The growth of hemp planted in soil containing Cd (82 mg kg$^{-1}$), chromium (Cr, 139 mg kg$^{-1}$), and nickel (Ni, 115 mg kg$^{-1}$) was not significantly affected. The accumulation of heavy metals in the hemp plant increased as the concentration of heavy metals in the hemp plant increased [14].

Hemp crops have a long development history around the world. They have the characteristics of multiplicity, extensive adaptability, strong resistance, and enrichment ability to heavy metals [15,16]. The main product of hemp is fiber, which does not enter the food chain and exhibits considerable economic value. Ramie (Boehmeria nivea L. Gaud) is known as “Chinese grass,” a perennial herbaceous plant grown in China with a long history. Ramie can be harvested three times per year in the Yangtze River basin, and its fiber is an essential resource for the textile industry. Ramie has the common characteristic of hemp plants. It has abundant values for the conservation and remediation of soil and water. Recent field surveys of non-ferrous metal mining areas in China’s Hunan, Guangdong, and Guangxi provinces demonstrated that ramie grows well in soils with high concentrations of Cd, Pb, or arsenic (As), and ramie has become a local dominant plant [17–19]. Further pot and field experiments demonstrated that ramie has strong resistance to heavy metals. The ability of ramie to adapt to the contaminated soils varies among different ramie varieties [20].

The removal of heavy metals from soils has become an urgent task in soil remediation. More effective strategies should be explored to remove heavy metal ions in soils. In the present study, we attempted to analyze the adsorption and translocation characteristics of different ramie cultivars to Cd and Pb. Seven main varieties of ramie were planted in farmland soils near a lead-zinc ore contaminated by heavy metals. The differences in adaptability, enrichment, and accumulation among ramie varieties to Cd and Pb were analyzed. Our study provided a new understanding of the use of ramie in the remediation of soils contaminated by heavy metal ions such as Cd and Pb.

2 Materials and methods

2.1 Ramie species

Seven main ramie varieties were selected and used in this work. Based on our previous experiment, these plants showed the potential ability to tolerate heavy metals. The cultivar names, origins, and characteristics [21] of the seven ramie varieties are listed in Table 1. All ramie varieties were provided by the Ramie Research Institute of Hunan Agricultural University.

2.2 Experimental location and soil properties

The study was conducted in the Tao lin lead-zinc mining area in Linxiang City, Hunan, China (113°18′ east longitude, 29°24′ north latitude) that was contaminated with Cd and Pb. The soil samples were collected from 0 to 20 cm depth of the experimental area and mixed using the five-spot-sampling method [22]. The basic characteristics (pH, total nitrogen, total phosphorus, total potassium, available nitrogen, available phosphorus, and available potassium) of experimental soil were determined using routine laboratory methods. Briefly, the soil pH was measured using an electrode-equipped pH meter in distilled water with a soil:water ratio of 1:2.5 (g mL$^{-1}$). Soil organic matter was determined using the K$_2$Cr$_2$O$_7$–H$_2$SO$_4$ oxidation method [23]. The total nitrogen, phosphorus, and potassium were determined using the Kjeldahl method, UV-1601 spectrophotometry, and flame photometry, respectively. Available nitrogen, phosphorus, and potassium were determined using the alkaline diffusion method, Bray method, and FP-640 flame photometry, respectively [24]. The content of Cd and Pb in the sample was determined using a SOLAAR M6 flame atomic absorption spectrophotometer [21]. The contents of Cd and Pb in soil were 5.55 and 156.64 mg kg$^{-1}$, respectively. Other soil properties are listed in Table 2. The Cd content in the soil exceeded China’s soil environmental quality grade II.
standard (0.3 mg kg⁻¹). However, the Pb content did not exceed the soil environmental quality secondary standard (300 mg kg⁻¹), it is much higher than the soil background value in Hunan province (35 mg kg⁻¹).

2.3 Experimental design and collection of samples

The ramie seedlings (25-day-old) were transplanted into the experimental field in August 2015. The experimental field was divided into 21 micro-regions (5 m × 2 m). Each plot contained 36 ramie plants, 7 ramie varieties were arranged in random blocks, and each variety had three repeats. The plots were managed in accordance with routine field management. Agronomic traits such as plant height, stem thickness, and skin thickness were measured, and plant and rhizosphere soil samples were collected during the ramie maturity period (June, August, and October 2016–2020). Ten cypresses were obtained from each plot of the plant samples. Soil samples from the 0 to 20 cm layer were obtained using the five-point sampling method [22].

2.4 Sample analysis

We separated the harvested ramie plants into roots, stem bone, husks, leaves, and raw fiber. They were then rinsed with tap water, rinsed with distilled water thrice, placed in an oven at 105°C for 15 min, and dried at 65°C to a constant weight. After crushing, they were passed through a 60-mesh nylon sieve for use. Once the soil sample was naturally air-dried and crushed, it was passed through a 100-mesh nylon sieve. The plant samples were digested via the nitric acid–perchloric acid method [25]. The soil samples were digested via the aqua regia-perchloric acid method [26]. The Cd and Pb contents in the sample were determined using a SOLAR M6 flame atomic absorption spectrophotometer (Thermo Fisher Scientific Corporation, USA). The enrichment coefficient, translocation coefficient, accumulation amount, extraction efficiency, and repair period were calculated using the following formula:

\[
\text{Enrichment coefficient} = \frac{\text{Metal concentration in shoot}}{\text{Metal concentration in soil}},
\]

\[
\text{Translocation coefficient} = \frac{\text{Metal concentration in shoot}}{\text{Metal concentration in root}}.
\]
Table 3: Agronomic traits and biomass of ramie grown on Cd- and Pb-contaminated farmland soils

<table>
<thead>
<tr>
<th>Variety</th>
<th>Plant height (cm)</th>
<th>Stem thickness (cm)</th>
<th>Skin thickness (mm)</th>
<th>Effective strain</th>
<th>Aboveground biomass (Mg ha(^{-1}) per year)</th>
<th>Raw fibre production (Mg ha(^{-1}) per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>138.27ab</td>
<td>9.27bc</td>
<td>0.60ab</td>
<td>6.47ab</td>
<td>15.72b</td>
<td>12.01b</td>
</tr>
<tr>
<td>2</td>
<td>128.57ab</td>
<td>8.67c</td>
<td>0.54b</td>
<td>8.58a</td>
<td>16.09b</td>
<td>12.49b</td>
</tr>
<tr>
<td>3</td>
<td>131.26ab</td>
<td>9.93ab</td>
<td>0.74a</td>
<td>5.76b</td>
<td>16.95b</td>
<td>16.51b</td>
</tr>
<tr>
<td>4</td>
<td>137.43ab</td>
<td>9.88ab</td>
<td>0.60ab</td>
<td>6.62ab</td>
<td>15.39b</td>
<td>13.45b</td>
</tr>
<tr>
<td>5</td>
<td>137.93ab</td>
<td>10.93a</td>
<td>0.69ab</td>
<td>6.67ab</td>
<td>20.71a</td>
<td>24.61a</td>
</tr>
<tr>
<td>6</td>
<td>157.51a</td>
<td>10.34ab</td>
<td>0.59ab</td>
<td>6.47ab</td>
<td>18.86b</td>
<td>15.01b</td>
</tr>
<tr>
<td>7</td>
<td>111.90b</td>
<td>10.12ab</td>
<td>0.68ab</td>
<td>7.04ab</td>
<td>14.86b</td>
<td>12.91b</td>
</tr>
</tbody>
</table>

Note: The average values in a column with different letters are significantly different at \(p < 0.05\) by multiple comparisons. Mg: megagrams; ha: hectare.

2.5 Statistical analysis

The data used in this experiment represent the average of six hemp seasons (over a two-year period). Experimental data were analyzed by Microsoft Excel 2016 and SPSS 17.0 software. Data were presented as the mean or mean ± standard deviation. We used an independent sample \(t\)-test or a one-way ANOVA to analyze the differences between groups for continuous measures. Statistical significance was considered at \(p < 0.05\).

3 Results

3.1 Growth of ramie in farmland polluted by heavy metals

To study the adaptability of different ramie varieties to Cd- and Pb-contaminated farmland, we analyzed the agronomic and economic characteristics of seven ramie varieties. Our results demonstrated that the plant height of the seven ramie varieties in Cd- and Pb-contaminated soil ranged from 111.90 to 157.51 cm, the average annual aboveground biomass was 14.86–20.71 Mg ha\(^{-1}\) per year, and the average annual raw fiber yield was 12.01–24.61 Mg ha\(^{-1}\) per year. Among the different varieties, the aboveground biomass and raw fiber yield of “Zhongzhu1” were 20.71 and 24.61 Mg ha\(^{-1}\) per year, respectively, which were significantly higher than those of other varieties (Table 3).

3.2 Distribution of Cd and Pb in various ramie organs

To understand the distribution of Cd and Pb in different tissues and organs of ramie, we further analyzed the Cd and Pb content in each organ of the ramie varieties and calculated the average Cd and Pb contents in each organ.
for all seven varieties. The general trend of distribution in each tissue of ramie is as follows: husks (26.54 mg kg\(^{-1}\)) > root (18.64 mg kg\(^{-1}\)) > stem bone (14.87 mg kg\(^{-1}\)) > leaf (11.09 mg kg\(^{-1}\)) > raw fiber (7.01 mg kg\(^{-1}\)). The Cd content in stem husks was significantly higher than that in other organs \((p < 0.05)\), and the Cd content in raw fiber was significantly lower than those in leaves, husks, stem bone, and roots \((p < 0.05, \text{Figure 1a})\). The overall trend of Pb distribution in each part of ramie can be arranged as follows: root (12.73 mg kg\(^{-1}\)) > leaf (12.12 mg kg\(^{-1}\)) > husks (10.86 mg kg\(^{-1}\)) > stem bone (3.59 mg kg\(^{-1}\)) > raw fiber (1.61 mg kg\(^{-1}\)). The Pb contents in the leaves, husks, and roots were significantly higher than those in the stem bone and raw fiber \((p < 0.05, \text{Figure 1b})\).

### 3.3 Accumulation and transportation of Cd and Pb in different ramie varieties

The aboveground Cd content of the seven ramie varieties ranged from 9.07 to 19.89 mg kg\(^{-1}\) with an average value of

![Figure 1](image-url)  
**Figure 1**: Content of Cd and Pb in the organs of different ramie varieties. (a) Cd content in the organs of different ramie varieties; (b) Pb content in the organs of different ramie varieties. Different letters above columns indicate significant differences (Tukey’s test, \(p < 0.05\)). Error bars indicate standard errors of the mean for \(n = 3\).
13.82 mg kg\(^{-1}\), while the root Cd content ranged from 11.65 to 28.63 mg kg\(^{-1}\) with an average value of 18.64 mg kg\(^{-1}\) (Table 4). The enrichment coefficient indicates the ability of plants to absorb from soil and accumulate heavy metals in their body. Generally, the larger the coefficient, the higher the enrichment efficiency of the plant. The enrichment coefficients of Cd in the aboveground parts and roots of seven ramie varieties are both higher than 1.0. However, the aboveground accumulation coefficients of “Zhongzhu1” and “Xiangzhu3” were 3.44 and 3.40, respectively, which were higher than those of other varieties. The enrichment coefficient in the roots of “Duobeiti1” was the highest (5.25), indicating that the aboveground parts of “Zhongzhu1” and “Xiangzhu3” and the roots of “Duobeiti1” had the strongest capacity for Cd adsorption from soil. The translocation coefficient (ratio of the heavy metal content aboveground to that of the root) indicates the ability of the plant to transport heavy metals from root to aboveground. In the present study, the average translocation coefficient of Cd for different ramie varieties was 0.76. Among all varieties, the Cd translocation coefficient of “Xiangzhu3” exceeded 1.11, which was significantly higher than those of other varieties. Therefore, “Xiangzhu3” has a strong ability to transport heavy metals upward.

The Pb content in the shoots and underground rhizomes of the seven ramie varieties was significantly lower than that in the rhizosphere soil. The enrichment coefficient of Pb for the shoots of seven ramie varieties was 0.04–0.06, with an average of 0.05. The enrichment coefficient of Pb in root was 0.05–0.10, with an average of 0.08, indicating that ramie has a weak ability to absorb significant amounts of Pb from the soil. The Pb content in the shoots of the seven ramie varieties is lower than in the underground rhizomes. The Pb translocation coefficient in each variety ranged from 0.39 to 0.93, with an average of 0.62, which is lower than 1.0, indicating that the ramie plant’s capability to transfer Pb from root to aboveground is weak (Table 5).

Table 4: Cd concentrations of different organs and enrichment translocation coefficient

<table>
<thead>
<tr>
<th>Variety</th>
<th>Cd content (mg kg(^{-1}))</th>
<th>Enrichment coefficient</th>
<th>Translocation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rhizosphere</td>
<td>Aboveground</td>
<td>Root</td>
</tr>
<tr>
<td>1</td>
<td>5.21</td>
<td>9.07d</td>
<td>14.60ab</td>
</tr>
<tr>
<td>2</td>
<td>5.30</td>
<td>10.69cd</td>
<td>11.65b</td>
</tr>
<tr>
<td>3</td>
<td>5.12</td>
<td>13.68d</td>
<td>21.55ab</td>
</tr>
<tr>
<td>4</td>
<td>5.43</td>
<td>18.47ab</td>
<td>16.63ab</td>
</tr>
<tr>
<td>5</td>
<td>5.79</td>
<td>19.89a</td>
<td>21.96ab</td>
</tr>
<tr>
<td>6</td>
<td>5.45</td>
<td>14.99bc</td>
<td>28.63a</td>
</tr>
<tr>
<td>7</td>
<td>4.64</td>
<td>9.96cd</td>
<td>15.47ab</td>
</tr>
<tr>
<td>Average</td>
<td>—</td>
<td>13.82</td>
<td>18.64</td>
</tr>
</tbody>
</table>

Note: The average values in a column with different letters are significantly different at \( p < 0.05 \) by multiple comparisons.

Table 5: Pb concentrations of different organs and enrichment translocation coefficient

<table>
<thead>
<tr>
<th>Variety</th>
<th>Pb content (mg kg(^{-1}))</th>
<th>Enrichment coefficient</th>
<th>Translocation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rhizosphere</td>
<td>Root</td>
<td>Aboveground</td>
</tr>
<tr>
<td>1</td>
<td>190.59</td>
<td>10.09bc</td>
<td>9.41a</td>
</tr>
<tr>
<td>2</td>
<td>146.60</td>
<td>12.33b</td>
<td>8.33ab</td>
</tr>
<tr>
<td>3</td>
<td>176.88</td>
<td>17.81a</td>
<td>7.79b</td>
</tr>
<tr>
<td>4</td>
<td>138.02</td>
<td>9.01c</td>
<td>7.21bc</td>
</tr>
<tr>
<td>5</td>
<td>161.00</td>
<td>16.15a</td>
<td>6.26cd</td>
</tr>
<tr>
<td>6</td>
<td>149.16</td>
<td>12.57b</td>
<td>7.36bc</td>
</tr>
<tr>
<td>7</td>
<td>137.21</td>
<td>11.18bc</td>
<td>5.82d</td>
</tr>
<tr>
<td>Average</td>
<td>—</td>
<td>12.73</td>
<td>7.45</td>
</tr>
</tbody>
</table>

Note: The average values in a column with different letters are significantly different at \( p < 0.05 \) by multiple comparisons.
3.4 Extraction capacity of different ramie varieties for Cd and Pb

The Cd accumulation in the underground rhizomes of the seven ramie varieties was higher than that in shoots, and the average accumulation of Cd was 2.19 mg shrub⁻¹ in the shoots and 3.37 mg shrub⁻¹ in the roots (Table 6). Significant differences were observed in the Cd accumulation among seven varieties. “Duobeiti” had the highest Cd accumulation in the roots (5.39 mg shrub⁻¹), followed by “Zhongzhu1,” in which Cd accumulation in the shoots and roots was 3.79 and 5.04 mg shrub⁻¹, respectively. Ramie is an herb with a perennial root age of 10–30 years. It can be harvested thrice annually, and its root system can reach up to 200 cm depths. Pb remediation is neither economical nor realistic by harvesting the underground parts of ramie. Accordingly, we primarily considered the remediation effect of aboveground parts. According to the remediation range of the 20 cm cultivated layer, the average Cd extraction efficiency for each variety is 1.84%. The average income from planting seven ramie varieties is 2,327 $ ha⁻¹ per year according to the market price of raw fiber (1.52 $ kg⁻¹) [27]. Planting “Zhongzhu1” is the best choice to remediate the soil contaminated by Cd based on the China soil environmental quality grade II standard in 0–20 cm cultivated layers, because it has the highest extraction efficiency of 2.95% with the shortest remediation period (about 31 years) and the highest income (3,748 $ ha⁻¹ per year, Figure 2).

The average Pb accumulation in the shoots (2.19 mg shrub⁻¹) of seven ramie varieties was lower than that in the roots (3.37 mg shrub⁻¹). The highest Pb was found in “Shiqianzhuugenma” (1.37 mg shrub⁻¹). According to the restoration range of the 20 cm cultivated layer, the average extraction efficiency of the aboveground parts of each variety is only 0.03%, while the difference between varieties is not significant. Considering that the Pb content in the soil of the experimental site did not exceed China soil environmental quality grade II standard, the remediation period of Pb in soil was not calculated.

4 Discussion

Soil contamination with heavy toxic ions has become a global concern [7]. Heavy-metal-tolerant plants can hyperaccumulate excessive amounts of Cd and Pb ions into the roots or aboveground tissues for the potential removal of chemical ions from soils [6]. Ramie is a unique fibrous plant and has a long history of cultivation in China. Ramie is widely distributed and possesses strong resistance to stress with significant biomass. Its fiber is mainly used for textiles without entering the food chain. Our study analyzed the agronomic characteristics and fiber biomass of different ramie varieties in Cd- and Pb-contaminated farmland soils and found that their agronomic traits and fiber biomass were not significantly limited compared with those grown in normal soils [28,29]. Appropriate field management allow ramie to adapt to mild levels of Cd and Pb.

The heavy metal ions absorbed by plants from their roots are then translocated to the stems, leaves, fruits, and other organs through the xylem [30,31]. Cd is distributed differently between different tissues and organs of the plant, resulting in preferential accumulation in the parenchyma and spore embryos [32,33]. Cd accumulation in the roots generally exceeds tissues such as the stems and leaves. Approximately 65–90% of Cd in most plants is present in the roots [34]. Our experiments showed that the Cd contents in each part of the ramie plant were as follows: root > stem and leaves > seeds. The concentrations of Cd in stems and leaves were as follows: husks > stem bone > raw fiber, while the Cd content in raw fiber and degummed ramie is extremely low [35]. In the present study, the distribution of Cd in each organ of ramie was as follows: husks > root > stem bone > leaf > raw fiber. The Cd contents were low in the raw fiber (Figure 1a), which contributed only approximately 9.02% of the plant’s aboveground mass (Table 3). Our results were consistent with previous findings [17,19,35], in which less Cd accumulated in the raw fiber section. Therefore, the proportion of Cd concentration contained in the raw fiber is negligible compared with those in the whole ramie plant. The harvested biomass (fiber) of ramie could be used for industrial purposes without considering the levels of heavy metals contained.

Most heavy metals are absorbed through the root system, while the other parts are enriched through the aboveground parts [36,37]. Several elements, such as Pb, mercury (Hg), and Zn, are primarily absorbed by plant leaves. Research on vegetables grown in polluted air showed that Pb content is high in rough leaves with large leaf areas. By contrast, leaves with small and smooth surfaces have low Pb content, indicating that more than 50% of Pb is absorbed from the dust through leaves [38]. Pb migration in rice is weak. After foliar spraying and Pb addition in to the soil, Pb is mainly concentrated in the leaves, roots, and stem of rice, acting as a barrier in the translocation of leaves and roots with the lowest Pb content [39]. In the present study, the overall trend of Pb distribution in each organ of ramie was as follows: root
Table 6: Cd and Pb accumulation and extraction efficiency of different ramie varieties

<table>
<thead>
<tr>
<th>Variety</th>
<th>Accumulation in root (mg shrub⁻¹)</th>
<th>Accumulation in aboveground (mg shrub⁻¹)</th>
<th>Annual extraction efficiency of the aboveground (%)</th>
<th>Relative repair time of soil cadmium (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cd</td>
<td>Pb</td>
<td>Cd</td>
<td>Pb</td>
</tr>
<tr>
<td>1</td>
<td>2.32b</td>
<td>1.63c</td>
<td>1.33c</td>
<td>1.37a</td>
</tr>
<tr>
<td>2</td>
<td>2.09b</td>
<td>2.315bc</td>
<td>1.59c</td>
<td>1.24ab</td>
</tr>
<tr>
<td>3</td>
<td>3.53b</td>
<td>3.02ab</td>
<td>2.11bc</td>
<td>1.21ab</td>
</tr>
<tr>
<td>4</td>
<td>3.21b</td>
<td>1.75c</td>
<td>2.60b</td>
<td>1.03ab</td>
</tr>
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<td>5.04a</td>
<td>3.67a</td>
<td>3.79a</td>
<td>1.19ab</td>
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<td>5.39a</td>
<td>2.38bc</td>
<td>2.62b</td>
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</tr>
<tr>
<td>7</td>
<td>1.98b</td>
<td>1.52c</td>
<td>1.32c</td>
<td>0.81b</td>
</tr>
<tr>
<td>Average</td>
<td>3.37</td>
<td>2.33</td>
<td>2.19</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Note: The average values in a column with different letters are significantly different at $p < 0.05$ by multiple comparisons.
> leaf > husks > stem bone > raw fiber. The Pb-containing dust emitted by the concentrators surrounding the polluted farmland could fall on the ramie leaves and be absorbed, resulting in high Pb content in ramie leaves, because Pb has poor mobility.

The Cd concentration of ramie shoots is generally higher than those of rhizosphere soil. The highest enrichment coefficient of Cd in ramie planted in 10 mg kg⁻¹ Cd-contaminated soil can exceed 5.8 [17,35]. However, the ability of different ramie varieties that accumulate Cd is different. Our study showed that the average Cd content in the shoots of seven ramie varieties was 13.82 mg kg⁻¹. The highest enrichment coefficient of Cd in the shoots of “Zhongzhu1” reached 3.44 after being planted in soil containing 5.79 mg kg⁻¹ Cd (Table 4). In this case, its fiber quantity and quality were not significantly affected, indicating that ramie can tolerate low concentrations of Cd stress [40]. The enrichment coefficient of Pb for the seven ramie varieties was only approximately 0.05, and the translocation coefficients were all less than 1.0. Therefore, most Pb is absorbed by the ramie plant and accumulates in the roots, which is consistent with the results of Yang et al. [41]. This phenomenon could also be related to the low plant availability of Pb in the soil [42]. Moreover, Pb in the root system mainly takes the form of precipitation, such as Pb₅(PO₄)₃ and PbCO₃, which are difficult to be transported to the aboveground because of adsorption, passivation, or precipitation [43,44].

According to the reference standard for hyperaccumulator proposed by Baker and Brooks [45], the heavy metal enrichment and translocation coefficients of hyperaccumulator grown in contaminated soil should both exceed 1.0. Meanwhile, its Cd and Pb concentration should exceed 100 and 1,000 mg kg⁻¹, respectively. In the present study, the enrichment coefficients of Cd in seven ramie varieties were all higher than 1.0, but the aboveground Cd content did not meet this standard. The annual extraction efficiency of Cd in the aboveground of “Zhongzhu1” reached 2.95%, which is far higher than those of Thlaspi arvense (0.6%) and Brassica juncea (0.5%) grown in soil [46,47]. The remediation of Cd contamination by planting “Zhongzhu1” may take approximately 31 years. Moreover, plants in Brassicaceae family are useful for phytoremediation because of their tolerance to high concentrations of heavy metals (40 mg Cd kg⁻¹), suggesting that white cabbage can be used for the phytoextraction of Cd-polluted soils [48,49]. However, unlike most plants used for phytoremediation, ramie possesses both high biomass and high economic value without entering food chains [19], generating 3,748 $ ha⁻¹ per year in income (Figure 2). Therefore, hyperaccumulators are not the only choice for the phytoremediation of heavy metals in contaminated soils. Economic plants such as ramie with significant biomass and the capacity to accumulate heavy metals can also be used to achieve the same goals. Moreover, many suitable ramie cultivars may help in the repair of contaminated soils and generate some income.

5 Conclusion

Seven ramie cultivars were observed to have good adaptability to contaminated soils with Cd (<5.79 mg kg⁻¹) and Pb (<190.59 mg kg⁻¹). The aboveground biological yield and raw fiber yield of “Zhongzhu1” were remarkably higher than those of other varieties. The Cd levels in each ramie part can be arranged as follows: husks > root > stem bone > leaf > raw fiber, while Pb levels in each ramie part can be arranged as follows: root > leaf > husks > stem bone > raw fiber. The extraction efficiency of Cd from the shoots of “Zhongzhu1” was 2.95%, which was significantly higher than those of other varieties. The extraction efficiency of Pb from each variety was much similar. Our results suggested that ramie can be used for the remediation of Cd- and Pb-contaminated soil at low concentrations. The best soil remediation effects and economic benefits could be obtained by planting “Zhongzhu1.” Our study provided a new understanding for the phytoremediation in lead-zinc mining areas. Further works are needed to clarify the transport mechanism of Cd and Pb in different tissues of ramie.

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References


[24] Wang J, Wang R. The physical and chemical properties of soil crust in straw checkerboards with different ages in...


