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Progress in the Study of the Absorption, Accumulation, and Tolerance of Ramie to the Heavy Metal Cadmium

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Abstract Ramie (*Boehmeria nivea*) is notable for its ability to accumulate and adsorb cadmium from heavy metal-contaminated soil. The accumulation of cadmium is more pronounced at a low cadmium concentration in the soil, and decreases with increase in cadmium concentration because of the effects of cadmium toxicity. In this review, the absorption, accumulation, and tolerance to cadmium of ramie is summarized. The existing knowledge gaps and prospects for utilization of ramie are noted to provide a theoretical foundation for future research on the utility of ramie for remediation of heavy metal-contaminated soil and for ramie breeding.

Keywords Ramie; Cadmium; Stress; Accumulation characteristics

Background

Ramie (*Boehmeria nivea*) is a perennial herb with large storage roots that is noted for its rapid growth, and high yield and quality of fibers. Ramie has been cultivated as a bast fiber crop in China since antiquity (Li et al., 2021). The ramie planting area in China is the largest in the world, hence ramie is often known as “Chinese Grass” (An et al., 2015; An et al., 2016).

The soil matrix contains diverse mineral elements with different properties and present in different proportions. From an environmental perspective, some elements are non-essential and harmful to organisms. The heavy metals cadmium, lead, arsenic, mercury, and chromium are the most toxic and common soil-contaminating elements (Lan et al., 2020). In recent years, the content of heavy metals in soil has increased sharply because of pollution from sewage irrigation, and overuse of chemical fertilizers and pesticides, for example. Contamination of soil with heavy metals has become a prominent impediment to socio-economic development in China. According to the Report on the National General Survey of Soil Contamination released by the Ministry of Environmental Protection in 2014, arable land in China has been contaminated with heavy metals to varying degrees, of which cadmium contamination accounts for approximately 43.5% of the total heavy metal contamination. These contaminants severely affect food security by impacting on grain, oil, fruit, and vegetable production in China. For example, of 160 polished rice samples purchased in the domestic market that were tested for cadmium content, 10% of the samples had a cadmium content of more than 0.2 mg/kg (Chen et al., 2018a).

Cadmium is among the most toxic heavy metal elements in the environment. Excessive cadmium in soil is susceptible to absorption and accumulation in plants, which not only causes decline in crop yield and quality, but also affects plant cell division, growth, and metabolic activities (Chen et al., 2021). In addition, after cadmium is absorbed by a plant’s roots, and accumulates in the leaves and various other tissues, it may enter the human body through the food chain, causing a variety of diseases and harming human health. The World Health Organization has classified cadmium as a Class I carcinogen (Nawrot et al., 2010).

China's arable land area per capita is small, but the demand for food is high. Safe agricultural utilization of heavy metal-contaminated arable land is important for food security, and for the quality and safety of agricultural products of the country. In recent years, many studies have focused on the main goal of safe utilization, involving soil improvement, selection and breeding of varieties with a low capability for heavy metal absorption, and agronomic management (Shen et al., 2016). Some studies have noted that ramie shows strong tolerance to heavy metals and thus is an ideal crop for remediation of soil with mild to moderate heavy metal contamination. Therefore, the potential use of ramie to prevent and control cadmium contamination is of practical importance (Su et al., 2021). Current research is mainly focused on the absorption and enrichment of cadmium, and the effects of cadmium on the growth, development, physiology and biochemistry of ramie (Liu et al., 2015; She et al., 2015; Chen et al., 2018b). This article reviews studies on the utilization of ramie for remediation of cadmium-contaminated soil and the response of ramie to cadmium stress. The aim is to provide a scientific basis for ramie remediation of cadmium-contaminated soil and for ramie breeding in the future.

1 Effects of Heavy Metals on Plants

1.1 Inhibition of plant growth and development

Heavy metals have inhibitory effects on the growth and development of plants (Asgher et al., 2015). For example, cadmium significantly inhibits the germination of alfalfa seeds. With increase in cadmium concentration from 5 mg/L to 40 mg/L, the germination frequency of alfalfa seeds decreases from 100% to 55% (Peralta et al., 2001). Cao et al. (2008) observed that chromium toxicity affects corn seedlings and significantly reduces the fresh weight and dry weight of seedlings; furthermore, the higher the cadmium concentration and the longer the treatment duration, the more marked is the toxicity effect. Wheat is the second largest food crop after rice in China. An excessively high concentration of cadmium causes toxicity effects on wheat, such as growth retardation, yield decline, and even crop death in severe cases (Wang et al., 2011). Zhang et al. (2009) reported that a zinc concentration of less than 100 mg/L and a copper concentration higher than 25 mg/L promotes the growth of alfalfa, whereas concentrations that exceed 600 mg/L and 400 mg/L, respectively, significantly inhibit seed germination as well as root and shoot growth of alfalfa.

The root system is the main organ through which plants absorb heavy metals from the soil. Heavy metals are harmful to cell structure, organelles, and root tips (Sengar et al., 2008), reduce root respiration, absorption of mineral nutrients, and production of adenosine triphosphate, and decrease peroxidase (POD) activity involved in plant growth and development, resulting in inhibition of growth (Aibibu et al., 2010). Experiments on the germination frequency and seedling growth of several garden plants, such as bermudagrass, tall fescue, and agrostis, under heavy metal stress showed that zinc and lead promote seed germination and seedling growth of seven species, including ryegrass, but have inhibitory effects on white clover. Cadmium promotes the growth of coreopsis, agrostis, bluegrass, and bermudagrass. Chen et al. (2018b) reported that, in rice, cadmium stress affects agronomic traits, reduces percentage seed set and grain weight, and decreases the shoot fresh weight and dry weight. Different concentrations of cadmium differentially affect seed germination (Rao et al., 2019). However, plant species vary in their responses to different intensities of cadmium stress; low concentrations of cadmium promote seed germination in some species, whereas high concentrations of cadmium inhibit seed germination in other species.

1.2 Effects on photosynthesis

During photosynthesis, the absorption and transfer of light energy is facilitated by photosynthetic pigments (Huang et al., 2020). The inhibitory effect of zinc on photosynthesis is mainly imposed by affecting the activity of chloroplastic enzymes, which accelerates chlorophyll decomposition (Liu and Hallenbeck, 2016). In severe cases, zinc disrupts chloroplast structure, causing loss-of-function by the chloroplast. Under zinc stress, the zinc content in the leaves is significantly negatively correlated with plant chlorophyll content (Hak et al., 2020). Many studies have shown that photosynthesis is inhibited by heavy metal ions. Chloroplasts are the site for photosynthesis. In land plants, chloroplasts are usually ellipsoid with smooth, flat surfaces and have a regular structure with at least three membrane systems. However, the ultrastructure is changed markedly under heavy metal stress. Cadmium stress disrupts the thylakoid membranes of chloroplasts in tomato mesophyll cells, and the volume increases significantly compared with that of the control, resulting in loss of chloroplast function and a distinct change in plant phenotype (Djebali et al., 2005).

1.3 Effects on nutrient absorption

In soil ecosystems, cadmium ions affect the uptake of soil nutrients and block the ion channels for essential elements, thus limiting the nutrient resources available to plants (Verbruggen et al., 2009). Exogenous nitric oxide reduces the toxicity of cadmium to plants (Li et al., 2018). Nitrogen fertilizers increase cadmium enrichment in plants (Wei et al., 2015). The increase in concentration of rapidly available phosphorus in the soil is mainly due to the activation of phosphorus-solubilizing microorganisms by root exudates and input of exogenous phosphorus. In addition, the protons and low-molecular-weight organic acids secreted during the process of phosphorus activation by the roots will activate phosphate ions and cadmium ions. The availability of cadmium increases with the rise in concentration of rapidly available phosphorus (Jafarnejadi et al., 2013). Rapidly available potassium refers to potassium that is readily absorbed and utilized by crops, including water-soluble potassium and exchangeable potassium. Liu et al. (2013) demonstrated that potassium deficiency protects rice seedlings from cadmium stress. Zhao et al. (2004) reported that in loamy soil (pH 7.7), addition of KCl and K_2SO_4 significantly promotes cadmium absorption by wheat. The roots are the first plant organ to be exposed to heavy metals. Heavy metals interfere with root absorption of nutrients from the soil, resulting in nutrient deficiency symptoms (Chen et al., 2019). The reason for this may be that heavy metal ions change the effective valency of mineral nutrients and the activities of nutrient absorption-associated enzymes in the plasma membrane of root cells.

2 Cadmium Absorption and Accumulation Characteristics of Ramie

2.1 Cadmium tolerance and effect of accumulation in ramie

Cao et al. (2004) studied the cadmium tolerance and accumulation effects on ramie in a pot experiment. The results showed that at the cadmium concentration of 200 mg/kg, the plants grew well and growth was promoted to a certain extent. The concentration of 900 mg/kg caused fatal toxicity effects on the plants, accompanied by rotting and hollow phenomenon of the plants. The plants died under exposure to cadmium concentrations higher than 200 mg/kg (Cao et al., 2004). She et al. (2014) explored the effects of different cadmium concentrations on cadmium absorption and accumulation by nine ramie varieties in a pot experiment. At cadmium concentrations of 23~46 mg/L, the aboveground biomass of the varieties Shiqian Zhugen Ramie, Yichun Hongxin Ramie, and Chuanzhu No. 1 was higher than that of the control (She et al., 2014). Planting ramie in cadmium-contaminated soil may contribute to soil remediation. Dai et al. (2003) reported that cadmium distribution in different organs, and cadmium contents in the root, stem, and leaf, of ramie plants differed among genotypes. The most highly significant difference observed was for Xiangzhu No. 2, in which the average cadmium content in the stem was as high as 11.98 mg/kg, which was more than four times that in the root. In addition, comparison of the cadmium contents of ramie shell, raw ramie, and ramie bone revealed that cadmium was mainly distributed in ramie shell; the variety with the highest cadmium content in ramie shell (as high as 74.56 mg/kg) was Shiqian Zhugen Ramie. Meng et al. (2012b) analyzed the growth response of ramie and the changes in heavy metal absorption, enrichment, and transfer characteristics under different concentrations of cadmium, antimony, and lead (Cd/Sb/Pb) applied in combination in a pot experiment. Exposure to high concentrations of Cd/Sb/Pb significantly inhibited the growth of ramie: the plant height was shorter and biomass was decreased. However, the combination of Cd/Sb/Pb at low concentrations had no significant effect on the growth and biomass of ramie. This study indicated that, compared with plants that produce low biomass, ramie is an ideal plant for simultaneous remediation of soil contaminated with Cd/Sb/Pb. Zhu et al. (2009) studied the tolerance and restoration potential of ramie grown in cadmium-contaminated soil in micro-plots. The cadmium content in raw ramie and in aboveground biomass increased with elevation in soil cadmium concentration. Under treatment with a cadmium concentration of 65 mg/kg, the enrichment coefficient was greater than 1. At a cadmium dose of 100 mg/kg, ramie plants retained the capability to complete the normal growth cycle and showed strong tolerance to cadmium. The aforementioned pot and field experiments show that cadmium at a low concentration has the effect of increasing ramie yield. Under a soil cadmium content of 10 mg/kg, agronomic traits and yield of ramie are improved. Cadmium contents in the soil of less than 100 mg/kg do not harm the agronomic traits of ramie, whereas at 200 mg/kg the various traits are decreased accordingly and at a soil cadmium content of 400 mg/kg ramie plants grow slowly, are shorter, and agronomic traits decrease to different degrees (Lin et al., 1996). Nevertheless, these results indicate that ramie is tolerant to cadmium and shows potential for phytoremediation of heavy metal-contaminated soil.

2.2 Cadmium enrichment and transfer ability of ramie

An important indicator that reflects the ability of plants to accumulate heavy metals is termed the enrichment coefficient. The higher the coefficient, the stronger the ability of the plant to accumulate heavy metals (Zhu et al 2018). Zhang et al. (2021) studied the cadmium enrichment ability of 269 ramie accessions grown in cadmium-contaminated cropland. Significant differences in cadmium accumulation and enrichment coefficients among the ramie accessions were observed. Meng et al. (2012a) showed that, with increase in cadmium treatment concentration, the enrichment coefficient of the aboveground biomass of ramie gradually decreases, which indicates that a high cadmium concentration is not conducive to cadmium transfer from the roots to the stems and leaves. However, at a cadmium concentration of less than 100 mg/kg, the enrichment coefficient of ramie plants is greater than 1, which indicates that, under exposure to a low concentration of cadmium, ramie plants show strong tolerance and enrichment ability.

The ratio of the content of a heavy metal in the aboveground organs to the content of the heavy metal in the roots of the same plant is called the transfer coefficient, which reflects the distribution of heavy metals to different organs of the plant (Lin et al., 2015). Generally, the higher the coefficient, the stronger the ability of the plant to accumulate the heavy metal. Meng et al. (2012a) reported that the transfer coefficient of ramie under different cadmium concentrations is less than 1. Under a concentration of less than 100 mg/kg, the transfer coefficient shows little variability and does not differ significantly from that of the control. With increase in cadmium concentration, the transfer coefficient decreases significantly and stabilizes at 300 mg/kg, at which the coefficient is reduced by 24.71% compared with that of the control. Zhu et al. (2018) studied differences in the growth and heavy metal enrichment of seven ramie varieties in contaminated cropland. All ramie varieties grew well, and the single-season biomass yield and raw ramie yield of Zhongzhu Ramie No. 1 were significantly higher than those of the other varieties. Significant differences in cadmium content in the aboveground biomass were observed among the varieties; the cadmium content in the aboveground organs of Zhongzhu Ramie No. 1 was 19.89 mg/kg. The extraction efficiency of cadmium from the aboveground biomass of Zhongzhu Ramie No. 1 was 2.95%, which was significantly higher than that of the other varieties. Thus, among tested varieties, Zhongzhu Ramie No. 1 offers the best soil remediation potential and economic benefits when using ramie for remediation of contaminated soil.

3 Effects of Cadmium on the Physiology and Biochemistry of Ramie

3.1 Effects on photosynthesis

Cadmium stress can reduce the transpiration rate of plants, leading to stomatal closure, thereby affecting the photosynthetic rate, inhibiting chlorophyll biosynthesis in the leaves, and ultimately affecting plant growth and development (Rui et al., 2016). Therefore, studying the effect of cadmium on plant photosynthetic physiology is extremely important. A study revealed that the cadmium treatment concentration is negatively correlated with photosynthetic rate (Liu et al., 2004); the growth of the four ramie varieties tested was promoted under a low cadmium concentration, whereas high concentrations inhibited growth. The stress caused by a low concentration of cadmium has a stimulatory effect on the synthesis of certain substances in ramie, thus promoting photosynthesis; however, the photosynthetic rate declines with increase in the cadmium concentration. Yan et al. (2007) observed that the intercellular carbon dioxide concentration of different cultivars was not significantly different among the treatments, indicating that the intercellular carbon dioxide concentration does not cause the change in photosynthetic rate under cadmium stress. Research showed that cadmium stress reduces the net photosynthetic rate, transpiration rate, and other photosynthetic indicators in leaves of ramie, resulting in a significant weakening of photosynthetic activity (Geng et al., 2011).

3.2 Effects on antioxidative enzyme activities

Enzymes are biocatalysts produced by all living organisms. Once antioxidant enzymes form oxides in the plant tissues, the enzymes will act immediately, using redox reactions to modify peroxides into less toxic or harmless substances. Therefore, the activity of antioxidative enzymes is important to reduce the toxicity of cadmium. Yang et al. (2016) found that the activities of superoxide dismutase (SOD) and POD of ramie under cadmium stress are more than 100 times higher in roots than in leaves; the difference in POD activity is the most distinct. The SOD activity of roots and leaves is negatively correlated with the duration of cadmium stress. The SOD activity of roots is enhanced with increase in cadmium concentration, whereas the SOD activity of leaves decreases with increase in cadmium concentration.

3.3 Effects on chelation

She noted that few studies have investigated the effects of cadmium chelation in ramie, but the principle of chelation is the same as that of other crops (Yang et al., 2016). The chelates in plants can bind with metal ions to form stable thiopeptide complexes, which can be transported to the cytosol or extracellular spaces by a translocator, thus representing an effective detoxification mechanism for protection from cadmium-induced damage (Wei et al., 2015). The research showed that the cadmium tolerance of ramie is essentially the result of chelation (Cao et al., 2012), which confers ramie with excellent properties for remediation of heavy metal-contaminated soil (Jafarnejadi et al., 2013). As a commercial fiber crop, ramie has the advantage over food crops of not entering the food chain.

4 Prospects

A major research focus in the multifunctional improvement of ramie is the remediation of cadmium-contaminated soil. The advantages of ramie include its strong cadmium tolerance, ready survival, and high biomass productivity. Ramie germplasm resources are relatively abundant and there is marked variation in the environment in which different varieties grow in different regions of China. Therefore, selection of varieties suitable for planting in cadmium-contaminated soil in different regions is desirable.

Research on the remediation of cadmium-contaminated soil with ramie is in its infancy. Insufficient basic research and technical bottlenecks presently hinder the achievement of substantial breakthroughs. In view of the current research status, we propose the following suggestions for future research. First, further investigation of the absorption and transport mechanism of heavy metals in ramie is required, in conjunction with targeted improvement of ramie using genetic engineering technology, selection of new varieties characterized by rapid growth, a well-developed root system, strong ability to absorb heavy metals, and strong tolerance to heavy metals, for utilization in phytoremediation. Besides, overall innovation of remediation methods for heavy metal contamination and their utilization should be conducted, using ramie in combination with other chemical, physical, and biological methods to restore cadmium-contaminated soil, so as to achieve the broader objective of protection and management of soil ecosystems, and to further enhance the soil restoration capability of ramie.

Authors' contributions

AX was the main authors of the review, and completed the collection and analysis of relevant literature and the writing of the first draft of the paper. WJQ, LQ, YJY, ZHP, LXH, LWL, LTT, ZLN, ZGL, CCL participated in the analysis and collation of literature materials. All authors read and approved the final manuscript.

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