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Potential use of bamboo in the phytoremediation of heavy metals: A review

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SUMMARY

There are many literature sources focusing on the phytoremediation of woody plants, but there are only few dealing with the phytoremediation of bamboo plants. Phytoremediation technology has the advantages of little disturbance to the environment and low remediation cost. Bamboo mainly exists in tropical and subtropical regions. As an energy plant, bamboo has a fast growth cycle, large biomass, simple cultivation, high economic efficiency, and convenient harvesting, which highlights the advantages of bamboo in phytoremediation. In addition, bamboo plants have good tolerance and uptake ability to heavy metals and have high application potential and development value in uptaking heavy metal contaminated soil. However, due to climate, temperature and other reasons, bamboo cannot be widely planted in most countries. Research status of remediation of heavy metal contaminated soil by bamboo plants is summarized. The feasibility of its application in heavy metal contaminated soil is discussed in this paper. Aiming at the shortcomings of existing research, bamboo plants have a prospect in the field of plant phytoremediation for the future.

Keywords: *bamboo plants; phytoremediation; heavy metal, Phyllostachys, contamination*

INTRODUCTION

Bamboo is a group of giant woody grasses whose natural habitat is roughly between 40 degrees south and north latitudes. It is widely found in Asia, the Pacific Islands, North and South America and Africa, excluding Europe (Bassam, 1998), with a total bamboo forest area of 31.5 million ha (FAO, 2010). China has the richest bamboo resources in the world, with more than 500 species belonging to 39 genera. It is also the origin and distribution center of bamboo (Zhou et al., 2011). In China, bamboo is used as a construction resource. However, few articles have been written about the use of bamboo for phytoremediation. In recent years, international scientists have begun to focus on the uptake and transport of heavy metals in soil by bamboo (Ranieri et al., 2020; Go et al., 2021; Chua et al., 2019). With the deepening and popularization and application of phytoremediation technology, the research focus has gradually shifted to the tolerance and accumulation of heavy metals in bamboo plants. In Kenya, phytoremediation has been used in specific cases (Were et al., 2017). Su et al. (2013) also found that the contents of Cu, Zn, Pb and Cd in bamboo rhizosphere soil were significantly lower than those in non-rhizosphere soil. Moso bamboo (*Phyllostachys edulis*) is the most widely planted bamboo species with the largest bamboo forest area in China and has attracted the highest research attention.

Phytoremediation is the use of plants and associated soil microbes to reduce the concentration or toxic effects of contaminants in the environment (Ali et al., 2013). Compared with physical and chemical remediation methods, phytoremediation technology is considered to be a heavy metal pollution remediation measure with many advantages, such as motionless remediation, low cost, environmental friendliness, no secondary pollution, and landscape enhancements (Weber et al., 2001). Phytoremediation includes phytoextraction, phytostabilization, phytofiltration, phytovolatilization, etc (Sarwar et al., 2017). Exposure to heavy metal stress shifts the plant from normal to defensive metabolism, and normal growth is inhibited (Jiang & Zhao, 2001).

EFFECTS OF HEAVY METAL STRESS ON BAMBOO

Effect of heavy metals on photosynthesis in bamboo plants

Under heavy metal stress conditions, damage to the chloroplast structure of bamboo plants by heavy metals will directly lead to a reduction in photosynthetic efficiency and, in severe cases, to plant death (Jiang et al., 2013). Ma et al. (2019) studied the effects of different concentrations of chromium on photosynthetic gas exchange parameters and chlorophyll fluorescence parameters in pot experiments. The results showed that relative chlorophyll content, net photosynthetic rate (Pn), stomatal conductance (Gs) and transpiration rate (Tr) all increased first and then decreased with the increase of chromium concentration, but the intercellular carbon dioxide concentration (Ci) showed the opposite trend. Zhang et al. (2011) explored effects of lead stress on the absorption and distribution of mineral nutrients in monopodial bamboo (*Pleioblastus amarus)*. The contents of calcium (Ca), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B) and molybdenum (Mo) in different organs were determined. The results showed that with the increase of lead, mineral nutrient contents in each organ changed significantly. Chen et al. (2015b) studied the Cu^{2+} tolerance mechanism of moso bamboo (*Phyllostachys edulis*) and found that when Cu^{2+} content exceeded 100 mg kg^{-1}, chlorophyll synthesis was significantly inhibited, and chlorophyll B was significantly more affected than chlorophyll A.

Copper ion also inhibited chlorophyll synthesis. In addition, in other species such as *Phyllostachys auresulcata* and *Pleioblastus chino,* as the heavy metal content increased, the net photosynthetic rate, stomatal conductance and electron transport rate of plants decreased and photosynthesis was significantly inhibited (Jiang et al., 2013). In addition to the obvious damage of chloroplasts, the high concentration of Zn ions also resulted in the disappearance of endoplasmic reticulum, the shrinkage of nucleus and nucleoli, and the disappearance of thylakoid membrane (Chen et al., 2014b; Liu et al., 2014).

Growth and development of Bamboo under heavy metal stress

When heavy metal content in soil is excessive, bamboo plants will show obvious symptoms of damage, such as yellow leaves, sparse branches and leaves, sudden reduction of biomass and bamboo shoots (Jiang, 2009). Chen et al. (2014a) examined the effects of four heavy metals (Pb^{2+}, Zn^{2+}, Cu^{2+} and Cd^{2+}) stress on seed germination of moso bamboo (*Phyllostachys edulis*), and the accumulation of heavy metals in different tissues of moso seedlings. The results were as follows: Pb^{2+} and Cd^{2+} inhibited the germination rate, germination potential, germination index and viability index of bamboo seeds. Cu^{2+} and Zn^{2+} promoted the germination potential, germination rate and germination index of moso bamboo seeds at low concentration (10 μmol L^{-1}), but significantly inhibited the germination rate at high concentration. When the concentration of Cd^{2+} reached 1600 μmol L^{-1}, the inhibition effect of Cd^{2+} on seed germination was stronger than the other three elements.

The germination rate and germination index of moso bamboo seeds increased under the conditions of low soil heavy metal content. However, with the increase of heavy metal content, the growth and development level and resistance of seeds will decrease, so the toxic effect of heavy metals on seeds will gradually increase (Chen et al., 2015a). Zhang et al. (2012) found the effects of Pb^{2+} and Cd^{2+} concentrations on seed germination were different but showed certain regularity. The effect of Pb^{2+} on the germination rate of bamboo seeds showed that with the increase of Pb^{2+} concentration, the germination rate increased first and then decreased.

Ability of bamboo plants to enrich for heavy metals

Bioconcentration factor (BCF) refers to the ratio of the content of a substance in the organism to the amount in the environment, which can be used to evaluate the ability of plants to uptake and accumulate a certain heavy metal. The higher the BCF value, the stronger the uptake ability of plants to heavy metals. In general, the uptake capacity of bamboo plants for heavy metals increases with the increase of soil heavy metal content (Were et al., 2017).

Table 1: **Field experiment with *Phyllostachys edulis* & *Phyllostachys praecox* exposed to heavy metal ions (Bian, 2018)**

		Phyllostachys edulis			***Phyllostachys praecox***		
	Heavy Metal	**Cu**	**Zn**	**Cd**	**Cu**	**Zn**	**Cd**
Content (mg kg^{-1})		99	3608	11	195	2980	14.5
BCF	**Root**	0.60	0.46	0.42	0.47	0.71	0.23
	Rhizome	0.36	0.41	0.40	0.43	0.60	0.26
	Stems	0.17	0.44	0.37	0.14	0.77	0.19
	Leaves	0.26	0.52	0.40	0.47	0.55	0.23
TF	**Rhizome**	0.60	0.89	0.95	0.91	0.85	1.13
	Stems	0.28	1.04	0.80	0.30	1.08	0.83
	leaves	0.43	1.13	0.95	1.00	0.77	1.03

Table 2: **A hydroponic experiment with *Phyllostachys heterocycle & Pleioblastus fortunei* exposed to heavy metal ions (Li et al., 2016; Chen et al., 2015; Liu et al., 2015; Zhang et al., 2011)**

		Phyllostachys edulis				***Pleioblastus fortunei;***
	Heavy Metal	**Cu**	**Zn**	**Cd**	**Pb**	**Pb**
Content (mg kg^{-1})		400	400	120	400	3315
BCF	**Root**	3.04	21.60	1.33	10.70	1.89
	Rhizome					0.50
	Stems	5.92	5.03	1.10	1.20	0.43
	Leaves	0.67	2.60	0.38	0.37	2.48
TF	**Rhizome**					0.26
	Stems	1.95	1.04	0.83	0.11	0.23
	Leaves	0.22	1.13	0.29	0.03	1.31

According to *Table 2*, the results showed that the BCF value for Pb were 1.89 and 2.48 for roots and leaves, respectively, and the uptake ability of stem and rhizome was relatively weak and heavy metals tend to accumulate rather in the root than in the other parts of the plant. In addition, the same bamboo species has different uptake capacities for different heavy metals. For instance, in the hydroponic experiment, the uptake ability of Cu and Zn is obviously better than that of Pb and Cd. The Pb uptake capacity of *Phyllostachys praecox* was analyzed by hydroponic and soil experiment (Li et al., 2014). The maximum concentrations of Pb in leaves, stems and roots were found to be 6706, 3710 and 26388 mg kg^{-1} under 100 μmol L^{-1} hydroponic Pb, respectively. when the lead content in soil experiments was 1200 mg kg^{-1}, the maximum uptake of lead in leaves, stems and roots was 63, 101, 595 mg kg^{-1} respectively (Li et al., 2014).

Distribution of heavy metals in bamboo plants

Transfer factor (TF) is the ratio of the metal content in the aboveground part of a plant to the metal content in the underground part. It is used to evaluate the transport and uptake capacity of heavy metals from underground to above ground (Were et al., 2017).

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Jiang et al. (2020) showed that the retention of Pb by the root system is one of its detoxification mechanisms to avoid damage to the shoots. In addition, the cytoderm retention is the dominant detoxification strategy of new roots, old roots, and new/old stems, while vacuole segregation was the detoxification strategy for new/old leaves. Meanwhile, Zhong et al. (2017) found different transport path of Pb^{2+} in different bamboo species.

In terms of *Phyllostachys edulis*, biomass can be accounted for over 90% of the entire bamboo, and the rhizomes can grow underground and spread over great distances (Yen & Lee, 2011). In bamboo forests, it is difficult to remove whole bamboo plants, removal of heavy metals mainly relies on multiple harvests of the aboveground parts. Therefore, the heavy metal content in the aboveground parts of *Phyllostachys edulis* directly affects soil heavy metal remediation efficiency. The BCF value of all part of *Phyllostachys edulis* was low, but the TF values of *Phyllostachys edulis* are high and show great potential in the application of heavy metal contaminated soil (Fan et al., 2018).

As for the underground biomass of *Pleioblastus fortunei*, it can account for 50% of the total biomass of the plant, and most of the rhizomes are in clusters, so it is easier to remove the whole plant. Despite the low TF value, the BCF value of the underground part is high (Zhang et al., 2011). Investigation with hydroponic experiment revealed that *Pleioblastus fortunei* had strong potential for Pb uptake, with TF value in leaves reaching 1.31 (Duan et al., 2019).

DAMAGE MECHANISM OF HEAVY METALS ON BAMBOO

The toxicity of heavy metals in plants may have two biological pathways (Zhang, 1997). First, a large number of heavy metal ions enter the plant, disturbing the original equilibrium system between ions, causing disorders in the uptake, transport, osmosis and regulation of normal ions, and disrupting metabolic processes. Secondly, when heavy metal ions enter plants, they not only bind to nucleic acids, proteins, enzymes and other macromolecules, but also replace specific elements necessary for some enzymes and proteins to perform their functions, denaturing them or reducing their activity (Chen et al., 1998).

Effects of heavy metal stress on active oxygen metabolism of bamboos

In healthy plant cells, the production and removal of ROS (reactive oxygen species) is balanced. Under stress, the ability to utilize CO_2 is inhibited through metabolic pathways such as photosynthetic electron transport and respiratory electron transport. When the production of ROS exceeds the scavenging capacity of its metabolic protective enzyme system, the balance of intracellular ROS production and clearance is disrupted, and the plant ROS metabolism is out of balance (Zhang et al., 2013).

Both in *Sasa auricoma* and *Sasa fortunei* reactive oxygen production was induced under the influence of heavy metal stress (Wang et al., 2010). Excessive reactive oxygen production in the early stage of stress activates the antioxidant enzyme activity in the plant and reduces the content of reactive oxygen, but with the accumulation of stress time, the concentration of reactive oxygen increases (Wang et al., 2010).

Effects of heavy metal stress on membrane lipid peroxidation of bamboos

The cell membranes of plants are considered as primary sites of damage due to heavy metals, and membrane instability was frequently attributed to lipid peroxidation. Large number of reactive oxygen radicals in plant tissues under stress cause lipid peroxidation of cell membrane, which disrupts the normal structure and function of membrane. MDA (malonaldehyde) is an oxidized product of membrane lipids, which is commonly considered general indicator of lipid peroxidation as well as stress level (Chen et al., 2015b). Jiang et al. (2013) irrigated two bamboos species with copper solution and found that with the increased copper solution, the percentage of senescent shoots and MDA content increased, while chlorophyll content and photosynthetic capacity decreased. After comparing the uptake of Cu ions by two bamboo species (*Phyllostachys auresulcata* and *Pleioblastus chino*), *Pleioblastus chino* showed a stronger intake capacity of Cu ions. As heavy metal stress increased, bamboo plasma membrane permeability increased, biofilms were severely damaged, peroxidized lipid MDA content increased, and the degree of membrane lipid aggravation and membrane structure disruption occurred the more the stress time increased. However, in *Sasa fortunei* under heavy metal stress, MDA content showed a decreasing trend (Ying et al., 2011).

Effects of heavy metal stress on the bamboo antioxidant enzyme system

Heavy metal stress can induce protective effects of plant antioxidant enzyme systems. With the enhancement of stress level and the extension of stress time, the activity of superoxide dismutase (SOD) of bamboo increased first and then decreased under heavy metal stress (Liu et al., 2018). *Sasa auricoma* showed an overall typical "N" type (increase/decrease/increase) trend under heavy metal (Zn, Cu) stress (Wang et al., 2010). Under the condition of heavy metal (Zn, Cu) stresses, reactive oxygen metabolism increases in plants, and superoxide dismutase (SOD) plays a key role in antioxidant system's first line of defense. The superoxide dismutase (SOD), peroxidase (POD), catalase (CAT) and lipid peroxidation products (MDA) of two dwarf bamboo species, *Sasa auricoma* and *Arundinaria fortunei*, were studied by potting method under various heavy metal stresses (Cd, Pb, Cu and Zn) (Wang et al., 2010). The results showed that with the increase of heavy metal concentration, the activities of SOD, POD and CAT increased first, then decreased, and finally increased ("N" type change). The trend of MDA changes was opposite to the trend of enzyme activities. Zhong et al. (2017) found, in moso bamboo (*Phyllostachys edulis*) that TBARS (Thiobarbituric

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acid-reactive substances) concentrations and SOD activities decreased with increase of Pb treatments. The activities of POD increased with increasing Pb treatments and reached peak level with application of 400 μM Pb.

Cai et al. (2021) treated *Sasa argenteostriata* with a high concentration of lead, and the bamboo could regulate both enzymatic and non-enzymatic systems to synergistically overcome the lead damage.

Guo et al. (2017) found that in moso bamboo (*Phyllostachys edulis*) rhizosphere soil, there was no significant correlation between heavy metals and soil enzyme activity, except for a significant negative correlation between available Pb and catalase. In non-rhizosphere soils, available Cd was significantly negatively correlated with catalase and urease, while Zn and Cd were not significantly correlated with soil enzyme activity.

Effects of environmental stress on osmotic regulation system of bamboos

Proline (Pro) and soluble sugars are important osmotic factors in plants and play an important role in regulating bamboo metabolism under environmental stress (Zhang et al., 2011). Plant cells increase intracellular Ca^{2+} concentration after being stimulated by the environment, forming a calcium concentration gradient with extracellular cells, producing calcium signal. Salt, drought (Dang et al., 2017), hypoxia and low temperature can cause an increase in calcium concentration, calcium signal transmission to calcium receptor through calcium channels, regulating a series of changes in plants (Zhang et al., 2006). The effect of heavy metal stress on the osmoregulatory system of bamboo has not been studied much, but there are some other articles, *Dendrocalamus latiflorus*, *Pleioblastus kongosanensis*, *Sasa fortunei*, *Sasa argenteostriatus*, *Pleioblastus fortunei* under drought stress (Li et al., 2010; Zhao et al., 2010) and *Oligostachyum lubricum* under the stress of ozone (Zhuang et al., 2011). The proline level of different bamboos showed different trends under various stresses. It was found that the soluble protein content was closely related to the cold resistance of bamboo (Liu et al., 2018). In general, bamboo species with strong cold resistance had high proline content, while the bamboo species with weak cold resistance had low proline content. The contents of proline, soluble sugar, and soluble protein can also reflect the difference in bamboo's tolerance to environmental stress to some extent. However, studies on the regulation of osmotic stress in bamboo under heavy metal stress are scarce.

STRENGTHENING MEASURES

Intercropping

Currently, most experiments are conducted in laboratory hydroponics or pot culture. Field experiments are necessary for studying of intercropping systems. Although field experiments have great limitations and uncertainties, the ultimate goal of phytoremediation is to implement it in contaminated areas. Bian et al. (2017) investigated the use of an intercropping model of moso bamboo (*Phyllostachys edulis*) and *Sedum plumbizincicola* to treat heavy metal contaminated soil. The intercropping pattern better promoted the uptake of heavy metal ions by the bamboo compared to the control group. Similarly, Bian etal. (2017) studied the microenvironment of bamboo monoculture and intercropping with *Sedum plumbizincicola*, and he found that intercropping increased bacterial α-diversity index and the number of biomarkers. Intercropping reduced the contents of soil organic matter (SOM), available nutrients, Cd and Cu in rhizosphere soil, and Cd and Zn in seed. The contents of Cd and Zinc in bamboo tissues increased after intercropping (Bian et al., 2021). Wu et al. (2016) used the crop rotation method of *Phyllostachys edulis* and *Dictyophora echinovolvata* to prevent bamboo forest decline due to the soil cover and increase the revenue. Therefore, the crop rotation mode of interplanting *D. echinovolvata* after landcover of moso bamboo, is a sustainable development of forests.

Additive

EDTA is a commonly used chelating agent which can form chelates with a variety of metal ions. In agriculture, the addition of EDTA can promote the uptake of metal ions by plant roots (Liu et al., 2015). Similarly, some researchers have used EDTA in phytoremediation. Zhang et al. (2018) compared the effects of EDTA and citric acid on heavy metal accumulation, toxicity and growth in bamboo and found that EDTA was effective in improving the content of heavy metals in bamboo aboveground. Although citric acid was also effective, EDTA had better remediation potential and improvement effect on bamboo than citric acid. Jiang et al. (2019) explored the tolerance behavior of bamboo to Pb^{2+} contaminated soil and discussed the effect of EDTA on phytoremediation. He treated five dwarf bamboo species with lead containing solutions of different concentrations and different EDTA concentrations and found that EDTA increased the absorption of Pb^{2+} by all parts of bamboo.

There are other additives, phosphogypsum, sepiolite, acetic acid, citric acid and other amendments can adjust soil properties, improve soil composition, can change the heavy metal uptake by plants from the soil, which is beneficial to the growth of bamboo (Yang et al., 2012).

Jiang & Xu (2005) explored different *Phyllostachys praecox* fertilization methods and soil available heavy metals in different months. The results showed that the effective levels of all five heavy metals (Pb, Cd, Zn, Cr, Cu) were higher in August, and then decreased significantly, and increased again in next April. Biochar, as a new material, has been used in phytoremediation. Wang et al. (2019) studied the effects of different proportions of wood biochar, bamboo biochar, rice straw biochar and Chinese walnut shell biochar on treatment of heavy metal contaminated bamboo forests. The results showed that all biochar, except bamboo charcoal, increased the uptake of heavy metal ions by bamboo roots.

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Land cover

The surface cover by straw, bamboo leaves, rice chaff and sawdust in bamboo forest in winter can enrich the heavy metals contents. The contents of Pb, Cr and Zn in the mulched area were 1.59, 1.30 and 1.26 times higher than those in the non-covered area, respectively (Li, 2016; Jiang & Xu, 2005). In addition, mulching can effectively increase soil nutrient content, improve forest productivity, and indirectly increase the extraction amount of heavy metals by plants (Chen, 2015).

But Yang & Xu (2003) concluded that soil properties changed considerably over time. The content of soil organic matter increased, the carbon to nitrogen ratio increased, and the accumulation of soil phosphorus was high. Soil peroxidase and phosphatase activities decreased significantly. The content of Zn, Cu and Pb in the soil showed an increasing trend and their bioavailability in the soil increased significantly. Yang & Xu (2003) attributed this result to heavy irrational fertilization and continuous winter surface cover of *Phyllostachys praecox* forest.

SUMMARY AND PROSPECTS

At present, the use of bamboo as a resource for phytoremediation is still in its infancy. However, due to its high biomass, bamboo has a certain ability to remove heavy metals in soil. Compared with super-accumulation plants, bamboo plants have great economic advantages. Not only is the input cost low, but the bamboo can also be used for landscaping. In the one hand, current research has focused on common heavy metal ions such as lead, zinc and copper, the screening of some bamboo species (Zheng et al., 2011; Li & Gao, 2015; Pan et al., 2019). On the other hand field experiments were also rare, and the main test sites were greenhouse experiments. The mechanism of uptake, transport and detoxification of heavy metal ions in bamboos is still unclear. In the future, we should explore the uptake ability of heavy metals of other bamboo species, select the best bamboo species, and conduct in-depth research on planting methods and other management measures.

The possibility of using bamboo for phytoremediation in Hungary

The use of bamboo for phytoremediation in Hungary has many limitations, such as precipitation, temperature, humidity, etc. Take moso bamboo as an example, climatic requirements are annual precipitation of 800–2050 mm most of which should fall in vegetation period, annual temperature of 15–20 degrees Celsius, air relative humidity of 70%–80%, soil requirements are slightly acidic sandy loam, pH between 4.5–7.0 (Xu & Qin, 2003). According to the relevant climatic data of Hungary (Kocsis, 2018), the planting conditions of moso bamboo is quite difficult. Solutions could include phytoremediation in a greenhouse, or finding other bamboo species that are hardy to cold and drought. Pan et al. (2019) and Kisvarga et al. (2021) explored the productivity and regeneration capacity of different bamboo species, which laid a foundation for selecting bamboo species with high biomass for phytoremediation.

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