

Discussion on the Application of *Sphagneticola trilobata* in Soil Heavy Metal Remediation

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Abstract This paper reviews the biological characteristics of *Sphagneticola trilobata* and the current research progress on its heavy metal accumulation. The species exhibits strong tolerance and accumulation abilities for heavy metals, including Cd, Hg, and Zn. Cd mainly accumulates in the leaf veins, thereby mitigating damage to the photosynthetic organs. Although its heavy metal accumulation capacity is inferior to that of hyperaccumulator plants, effective remediation can be achieved through a strategy emphasizing "quantity compensating for quality" combined with multiple mowing. Meanwhile, the risk of invasion by *S. trilobata* can be managed through approaches including engineering isolation, community configuration, and hybrid breeding. This paper seeks to establish a theoretical foundation for the use of *S. trilobata* in the remediation of soils contaminated with heavy metals. Its objective is to advance the development and application of phytoremediation technologies and to enrich the existing phytoremediation system for soils contaminated with heavy metals. Furthermore, the study identifies directions for future in-depth research on strategies for "treating pollution with harmful substances".

Key words *Sphagneticola trilobata*, Heavy metal, Phytoremediation, Soil pollution, Invasive plant

0 Introduction

Soil heavy metal pollution refers to contamination resulting from the excessive accumulation of heavy metals in the soil, primarily due to waste generated during industrial and agricultural activities as well as urbanization. The sources of these heavy metals can be categorized into natural and anthropogenic origins. Natural sources include atmospheric deposition, soil parent materials, and soil formation processes. In contrast, anthropogenic sources consist of industrial and agricultural activities such as mining, the application of pesticides and fertilizers, vehicle exhaust emissions, and urbanization processes. Research indicates that the extent of heavy metal pollution in soil has been continuously intensifying along with industrialization and urbanization, with the affected areas expanding annually^[1]. Heavy metal pollutants are resistant to microbial degradation once introduced into the soil. Their high accumulation can alter the soil's physical and chemical properties, resulting in significant soil degradation, environmental deterioration, adverse impacts on agricultural productivity, and potential risks to human health. Studies have shown that heavy metals in soil can disrupt the activities of protease and amylase, thereby inhibiting the germination of plant seeds^[2]. Heavy metal ions adsorb onto the cell walls of plant roots, affecting the transmembrane transport of Ca ions. This disruption prevents the activation of

calmodulin and Ca-ATPase, adversely affecting mitosis in root tip cells and consequently inhibiting plant growth^[3]. High concentrations of heavy metals in soil can inhibit the enzymatic activities within plant leaves, thereby suppressing the photosynthesis of leaves^[4]. These effects together contribute to a decline in crop yields.

Soil heavy metal remediation technologies mainly include physical remediation methods (such as soil replacement and thermal desorption), chemical remediation techniques (including chemical leaching, chemical fixation, and electrokinetic remediation), and biological remediation approaches (comprising microbial, animal, and plant-based methods). Although conventional physical and chemical remediation methods have high remediation efficiency^[5], they are often associated with drawbacks such as high costs, operational complexity, potential secondary pollution, and limited applicability^[6]. In contrast, phytoremediation has garnered considerable attention owing to its distinct advantages, including low cost and environmental friendliness. However, the hyperaccumulator plants that have been identified generally have limitations, including limited species diversity, low biomass, slow growth rates, and excessive selectivity for specific heavy metals, which hinder their large-scale engineering application. Hence, the potential to utilize the robust environmental adaptability and rapid reproductive capacity of invasive plants to compensate for the shortcomings of traditional hyperaccumulators has emerged as a prominent research focus in this field.

1 Phytoremediation technology and application potential of invasive plants

1.1 Enrichment mechanism of heavy metals in plants In 1983, the American scientist Chaney first introduced the concept

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of phytoremediation^[7]. This technology lowers the concentration of environmental pollutants by utilizing the ability of plants to absorb, transform, accumulate, or degrade pollutions. The accumulation of heavy metals by plants is a complex physiological process, primarily involving mechanisms such as rhizosphere effect, transmembrane transport mediated by metal transporters, complexation with plant chelating peptides, vacuolar compartmentalization, and cell wall binding and fixation^[8]. In recent years, researchers have employed various plant species, including flowers, herbaceous plants, crops, and woody plants, as experimental materials to study their capacities for accumulating heavy metals in soil. Hou Dandi^[9] suggested that *Sedum alfredii*, a plant known for its hyperaccumulation of Zn and Cd as well as its high Pb content, had strong tolerance and accumulation abilities for multiple heavy metals, making it a good candidate for the phytoremediation of contaminated soils. Tang Yetao *et al.*^[10] reported that *Arabis paniculata* had the capacity to accumulate excessive amounts of Pb, Zn, and Cd, thereby offering novel germplasm resources for the phytoremediation of soils contaminated with complex heavy metals. He Mengke *et al.*^[11] showed that *Amaranthus hypochondriacus*, *Brassica napus* 'Zhongyou 1000', and *Helianthus annuus* 'S606' exhibited significant potential for the extraction and remediation of the heavy metals Cd and Pb, with Cd removal rates exceeding 1.90% in the soil.

The fundamental approach to remediating heavy metal pollution in soil through phytoremediation involves the identification of hyperaccumulator plant species. However, the number of hyperaccumulator plants identified to date remains limited, and many exhibit challenges such as prolonged remediation durations, specificity to certain heavy metals, and limited tolerance to contaminated environments. Meantime, the use of edible hyperaccumulator plants has the potential to enter the food chain, thereby posing health and ecological risks. Therefore, few hyperaccumulator species are currently viable for practical application in remediation efforts. It is therefore worth investigating whether the advantageous traits of invasive plant species, including their robust reproductive and adaptive capacities, can be used to identify varieties capable of accumulating heavy metals for effective soil remediation.

1.2 Feasibility of invasive plants as restorative materials

Although hyperaccumulator plants have considerable benefits, their limited species diversity and prolonged restoration periods have constrained their practical engineering applications. Conversely, invasive plants, characterized by robust adaptability, rapid reproductive rates, and high biomass production, have emerged as potential alternative resources. These invasive species primarily reproduce asexually, facilitating rapid growth and proliferation, and frequently display pronounced allelopathic effects. The allelopathic compounds they release inhibit the growth of neighboring plants, thereby enabling the rapid spread and establishment of monocultures dominated by a single species^[12]. Some scholars have confirmed that invasive plant species can develop various mechanisms to withstand adverse environmental conditions over ex-

tended periods, thereby enhancing their tolerance. Zhou Qiwu *et al.*^[13] reported that *Ageratina adenophora* exhibited significant accumulation of heavy metals such as Cr, Mn, Hg, Ni, As and Sr, indicating its potential value in the remediation of heavy metal pollution. Zu Yuangang *et al.*^[14] investigated *Cyclachaena xanthiifolia* and confirmed its strong tolerance and accumulation capacity for Cu and Pb, suggesting considerable application potential in the phytoremediation of Cu and Pb contamination. Lin Maozi *et al.*^[15] found that *Alternanthera philoxeroides* showed good tolerance and enrichment abilities for Mn, Ni, Cr, Pb, Cu, and Zn. These studies provide a critical theoretical foundation and practical guidance for employing invasive plants in the remediation of heavy metal-contaminated soils through the strategy of "treating pollution with harmful substances".

2 Biological characteristics and restoration potential of *Sphagneticola trilobata*

2.1 Biological characteristics and adaptability to adversity

S. trilobata, a member of the Compositae family, is indigenous to Central and South America. Originally introduced as an ornamental plant, it produces naturally occurring volatile terpenoids that exhibit allelopathic effects, inhibiting the growth of neighboring plants and contributing to its extensive invasion in South China^[16]. The stem of *S. trilobata* is creeping, with the upper portion nearly erect. The leaves are opposite, shallowly trifid, serrated, and predominantly elliptical, elongated, or linear in shape. The leaf surface is glossy, with both sides covered with bristles, and the petioles are nearly absent. The stem is slender, smooth, and either glabrous or slightly pubescent. The capitulum is medium-sized, featuring yellow petals. This species has an extended flowering period, blooming year-round, with peak abundance during summer and autumn^[17]. The population primarily reproduces asexually, demonstrating rapid growth and reproduction, strong vitality, and considerable environmental adaptability. The local species *S. calendulacea*, belonging to the same genus, is also a perennial herbaceous clone and is widely distributed in southern China. These two species often coexist in the field. The primary distinction between them is that the leaves of *S. trilobata* are trifid, whereas those of *S. calendulacea* are predominantly lanceolate or oblong.

Li Wujun *et al.*^[18] reported that, compared to native species, *S. trilobata* exhibited greater survival competitiveness and broader adaptability to varying soil nutrient conditions. A reduction in soil nutrients did not significantly affect its biomass or root-to-crown ratio. Yuan Weiyang *et al.*^[19] found that under homogeneous nutrient conditions, the root biomass of *S. trilobata* was directly proportional to soil nutrient levels, offering a competitive advantage that facilitates its large-scale invasion. Under heterogeneous nutrient conditions, the species can adjust its growth strategy based on the spatial distribution of nutrient patches, thereby enhancing its competitiveness and promoting growth. This pronounced phenotypic plasticity and efficient resource utilization lay

the foundation for its survival and remediation capabilities in infertile, heavy metal-contaminated soils.

2.2 Characteristics and evidence of heavy metal accumulation In recent years, significant advancements have been made in understanding heavy metal accumulation of *S. trilobata*. Lin Maozi *et al.* [20] reported that *S. calendulacea* exhibited a strong absorption capacity for Ni, Cu and Cd. In addition, the concentration of heavy metals was found to be higher in the leaves compared to the roots and stems, suggesting that the accumulation of heavy metals in *S. calendulacea* mainly occurs in the foliar tissues. In addition, studies have showed that Cu pollution stress does not significantly reduce the aboveground biomass of *S. trilobata*, which is attributed to the maintenance of root activity and chlorophyll content under Cu stress. This can be inferred to be the physiological basis underlying the adaptability of *S. trilobata* to Cu-induced stress [21].

Aveiga *et al.* [22] confirmed that the invasive species *S. trilobata* had the capacity to accumulate Hg and Zn, exhibiting adsorption rates ranging from 43.49% to 59.22% for Hg and from 32.68% to 64.37% for Zn. Shi Heping *et al.* [23] investigated the physiological responses of *S. trilobata* hairy roots under Cd stress and found that Cd exposure significantly increased the soluble protein content as well as POD and SOD activities in the hairy roots, thereby mitigating the inhibitory effects and toxicity of Cd on root growth. Moreover, their study revealed that *S. trilobata* hairy roots exhibited a strong adsorption capacity for Cd, with the highest Cd ion adsorption observed at a culture concentration of 300 $\mu\text{mol/L Cd}^{2+}$. Huang Jundong *et al.* [24] exposed *S. trilobata*, *S. calendulacea*, and their hybrids to 200 $\mu\text{mol/L Cd}$ and observed distinct Cd distribution patterns among the three plant types. The Cd transport capacities varied, suggesting the presence of different transport mechanisms in these plants. In general, Cd is initially absorbed by the roots, transported upward through the stems, and ultimately accumulated in the leaves. The Cd absorbed by *S. trilobata* was mainly concentrated in the photosynthetic organs (leaves), with the highest accumulation observed in the veins, reaching up to 2 766.3 $\mu\text{g/kg}$. In contrast, the Cd absorbed by *S. calendulacea* and its hybrids was primarily concentrated in the stems. The Cd content in the leaves of all three plants exhibited a similar pattern of distribution, with concentrations following the order: veins > vein spaces > vein edges. Cd accumulation in plant leaves can cause damage to mitochondria and chloroplasts, affect ATP synthesis, and degrade photosynthetic pigments. Notably, the light reaction center is particularly susceptible to Cd-induced stress, which is closely associated with reductions in leaf photosynthetic efficiency as well as the efficiency of light energy conversion and utilization [25–26]. Studies have demonstrated that the localized accumulation of Cd in leaf veins can reduce its inhibitory effects on the photosynthetic capacity of other leaf regions. In consequent, the large accumulation of Cd in the veins of *S. trilobata* may alleviate the toxic impact of Cd on its metabolically active tissues [27]. In summary, *S. trilobata* exhibits

potential for use in the remediation of heavy metal pollution.

3 Advantages, challenges and regulatory strategies of the restoration application of *S. trilobata*

3.1 Advantages and bottlenecks as a repair material The identification criterion for hyperaccumulator plants requires that both the enrichment coefficient and the transport coefficient exceed one [28]. Although *S. trilobata* does not satisfy the criteria for hyperaccumulator plants [29], its rapid reproduction rate and large biomass compensate for its relatively low accumulation capacity per unit mass. Meanwhile, the stem segments of *S. trilobata* exhibit high malleability and can continuously extract heavy metals through repeated mowing, thereby enhancing remediation efficiency. As a result, employing *S. trilobata* as a pioneer species for the remediation of soil heavy metal pollution offers a novel approach for soil heavy metal treatment.

However, the application of this species faces two significant challenges. First, its pronounced allelopathic effects can inhibit the growth of neighboring species, resulting in insane invasion, which makes it unsuitable for large-scale cultivation. In comparison to *S. trilobata*, *S. calendulacea* exhibits a lower reproductive capacity. Therefore, it is worth investigating whether the reproductive capacity of *S. trilobata* can be reduced through hybridization, thereby enhancing its potential for use in soil heavy metal remediation and facilitating the development of new cultivars characterized by "low invasiveness and high accumulation" through hybrid breeding. Some studies indicate that the growth potential of the *S. trilobata* hybrid is slightly lower than or comparable to that of the invasive species, but the hybrid exhibits significantly higher energy utilization efficiency than its parent species [30]. Furthermore, there remains a lack of systematic evaluation regarding the tolerance and accumulation capacity of individual species in response to complex heavy metal pollution, despite the fact that contaminated sites are frequently affected by multiple heavy metals simultaneously. Besides, for the disposal of heavy metals in restored plants, it is necessary to address issues related to minimizing secondary pollution and enhancing the value of resource utilization.

3.2 Risk control and enhanced restoration strategies The invasion risk of *S. trilobata* can be managed through two primary approaches: engineering control and biological improvement. At the engineering control level, its growth can be confined to the soil areas requiring remediation by constructing physical barriers such as fences, sidewalks, or grass and stone isolation belts, thereby preventing the proliferation and spread of *S. trilobata*. *S. trilobata* should be removed prior to its peak growing period and rainy seasons to inhibit excessive growth and reproduction [31]. At the same time, *S. trilobata* can be cultivated alongside other species characterized by high biomass, strong adaptability, and heavy metal tolerance to inhibit its excessive proliferation [32]. When the concentration of heavy metals in the restored area drops to a certain extent, other hyperaccumulator species of heavy metals

may be introduced to replace *S. trilobata*, to control its spread and reduce its adverse effects on the ecological environment. At the level of product disposal, in order to reduce hazard risks and enhance resource utilization value, techniques such as pyrolysis, phytometallurgy, and hydrothermal modification can be employed to convert *S. trilobata* into materials like biochar, facilitating resource recovery^[33].

At the genetic improvement level, *S. calendulacea* displays a lower reproductive capacity compared to *S. trilobata*. The development of new cultivars characterized by "low invasiveness and high accumulation" through hybrid breeding is a highly promising approach. Research indicates that the growth potential of *S. trilobata* hybrids is slightly lower than or comparable to that of the invasive species, but their energy utilization efficiency is significantly greater than that of the parent species. Huang Jundong *et al.*^[24] have also reported that these hybrids demonstrate enhanced affinity for Cd migration. Thus, reducing the reproductive and dispersal capacity of *S. trilobata* via hybridization, while maintaining or improving its heavy metal accumulation capabilities, has considerable potential for applications in soil remediation. Currently, there are few studies examining the adaptability of hybrids and their parental species across diverse growth environments, as well as comparative analysis of their tolerance to various heavy metals, which is worthy of further in-depth investigation.

3.3 New technological means and application prospects At present, scholars at home and abroad often employ hydroponic or soil cultivation methods to study *S. trilobata*. However, these approaches are susceptible to external environmental influences and pose potential risks related to plant dispersal and ecological damage. In contrast, plant tissue culture, conducted under sterile conditions, mitigates the impact of external factors on plant growth, thereby allowing for the isolation of single variables during experimental investigations. This technique offers advantages such as rapid propagation, land conservation, controllable cultivation conditions, and shortened growth cycles. Utilizing tissue culture technology for in-depth studies on the heavy metal accumulation of *S. trilobata* enables large-scale propagation while preserving its genetic integrity and simultaneously minimizing the risks associated with species proliferation and ecological harm.

4 Conclusions and prospects

Based on the above analysis, *S. trilobata* shows significant potential for application in the remediation of soil contaminated with heavy metals, attributable to its high biomass, strong tolerance, and distinctive heavy metal compartmentalization and accumulation strategy. Although its accumulation capacity is inferior to that of typical hyperaccumulator plants, effective pollution remediation can be achieved through a strategy emphasizing "quantity compensating for quality" combined with multiple mowing. Concurrently, the risk of its invasiveness must not be ignored and should be mitigated through comprehensive measures, including engineering isolation, community configuration, and genetic improvement.

Future research should focus on the following areas: (i) the development of an efficient tissue culture and genetic transformation system for *S. trilobata*; (ii) the identification and analysis of key genes and regulatory networks involved in heavy metal tolerance and accumulation, alongside the implementation of molecular-assisted breeding; (iii) a systematic evaluation of the species' response and accumulation characteristics under complex heavy metal pollution; and (iv) the exploration of restoration models that integrate local species to promote ecological recovery concurrently with pollution remediation. Pursuing these research directions will provide a robust scientific foundation for utilizing invasive plants in the remediation of heavy metal pollution, advance the practical application of the "treating pollution with harmful substances" strategy, enhance ecosystem stability, support the integrated management of mountains, rivers, forests, farmlands, lakes, grasslands, and deserts, foster ecological restoration, and contribute to the comprehensive revitalization of rural areas.

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