RESEARCH PROGRESS IN THE SUSTAINABLE AND SAFE UTILIZATION OF CADMIUM-CONTAMINATED FARMLAND SOIL WITH LOW-ACCUMULATING MAIZE (*ZEA MAYS* L.) VARIETIES

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Abstract. Maize (*Zea mays* L.) is a crucially important crop, serving as both a feedstock and an industrial raw material. Intercropping, a traditional agronomic practice, enhances the efficient use of maize and improves the quality of co-planted crops by leveraging the concepts of niche differentiation and biodiversity. This method aims to mitigate heavy metal absorption in crops, thereby enhancing their yield and quality. It also seeks to achieve a dual goal of 'production and remediation,' optimize land use efficiency, and bolster economic returns. A literature review conducted in the Web of Science Core Collection database, focusing on maize and Cd-contaminated soil, revealed an increasing trend in citations and publications over time, indicating a growing research interest in these areas. This paper reviews the safe utilization of contaminated farmland soil under the intercropping system that combines hyperaccumulators with low-accumulation maize varieties. Additionally, it assesses the impact of intercropping on soil environmental quality. The paper also discusses the emerging trends in the application of intercropping for the remediation of heavy metal-contaminated soils, the utilization of phytoremediation biomass, and the development of efficient intercropping systems to enhance the remediation efficiency of such soils.
Keywords: *heavy metal, soil remediation, hyperaccumulator, intercrop, phytoremediation*

Introduction

Heavy metal pollution in farmland soil has become a serious environmental problem worldwide, constituting a significant threat to both food security and public health (Wang et al., 2021; Wang and Zhao, 2022; Du et al., 2020). Soil pollution control and remediation should prioritize bioremediation approaches that do not affect agricultural production and do not reduce the production functions of the soil. Phytoremediation technology has garnered significant attention due to its advantages, such as economic efficiency, environmental friendliness, in-situ remediation, and sustainability (Shah and Daverey, 2020). However, phytoremediation also has limitations; for instance, most hyperaccumulators grow slowly, have limited biomass, and possess little economic value (Odoh et al., 2019). The efficiency of remediation is not solely dependent on the plant itself but is also influenced by the biological availability of heavy metals in the soil (Sarwar et al., 2017). Concurrently, the application of phytoremediation technology

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faces numerous constraints, including economic considerations and extended remediation periods, which urgently require resolution.

It is inevitable to prevent and control soil pollution, ensure the quality of agricultural products and the safety of ecological environment, take green development as the guidance, coordinate and streamline efforts to achieve the objectives of resource efficiency, and that resources are used optimally, improving quality and increasing production, ensuring environmental safety and economic development, and promoting the sustainable development of high-quality agriculture is essential for our future (Zhang et al., 2020). Phytoremediation of heavy metal-contaminated soil has a long cycle. If agricultural cultivation is carried out after the contaminated soil is completely repaired, economic development will not be guaranteed. However, there may be health risks if general crops are directly planted in contaminated soil. Therefore, it is necessary to make scientific use of land with different environmental quality, taking into account yield and quality, and maximize economic and ecological benefits (Zhou et al., 2020). In order to realize the sustainable utilization of contaminated soil, the accumulation of heavy metals in edible parts of crops should be reduced as much as possible, so as to meet food security and ensure people's health.

The essence of soil safety utilization is the utilization of land resources. Therefore, the problem of technical cost must be considered and the promotion of safe utilization technology cannot become the burden of farmers and local governments (Li, 2019). Based on the ecological principle of ecosystems, different plant intercropping has different growth periods, functional traits and nutrient requirements, forming complementary niche advantages. In order to safely utilize contaminated soil and achieve 'production while repairing,' it is essential to build a 'win-win' intercropping system (Wang et al., 2023). Additionally, the involvement of plant growth-promoting rhizobacteria have piqued the interest of numerous scholars in the remediation of contaminated soils (Anitha et al., 2024), which is conducive to improving the sustainability of soil ecosystems.

Maize (*Zea mays* L.), a pivotal crop species, serves as a critical source of feed and industrial raw materials, underscoring its economic and nutritional significance (Stepić et al., 2022). The cultivation of maize in contaminated soils poses a significant challenge due to the potential accumulation of harmful elements, such as cadmium (Cd), which can compromise both environmental safety and public health. Therefore, the deployment of low-accumulation maize varieties represents a strategic approach to ensure the safety and sustainability of agricultural practices in such environments. This paper reviews the differences in the enrichment of heavy metals by different maize varieties, the application of maize and hyperaccumulators in the remediation of contaminated soil under intercropping conditions that taking China as an example, and the development trend of intercropping in the field of remediation of heavy metal-contaminated soil was prospected.

Screening of low heavy metal accumulation maize varieties

Plant barrier technology based on low heavy metal accumulation varieties is considered to be a promising and practical green remediation technology for farmland soil. The basic goal of safe utilization technology of contaminated soil is to prevent pollutants from entering the food chain (Li, 2019). The sustainable and safe utilization of low accumulation maize varieties in contaminated farmland soil as shown in figures

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(*Fig. 1*). Therefore, new crop varieties with less heavy metal uptake can be cultivated through genetic breeding, that to reduce the risk of heavy metals entering the food chain (Zhao, 2020; Stepić et al., 2022). Studies have shown that the use of low-accumulation rice varieties planted in light and moderate Cd-contaminated farmland has an average Cd reduction rate of 58%, which has a significant application effect (Wang et al., 2021), and can achieve safe production of crops and reduce health risks. The results of field investigations and literature data analysis supported that maize is a crop with low grain heavy metal accumulated. And the normal and waxy maize is prioritized over the sweet maize (Cao et al., 2019). Screening and cultivating crop varieties with low accumulation of heavy metals in edible parts that are lower than relevant food safety standards can ensure the safe production of agricultural products and the safe use of contaminated soil.

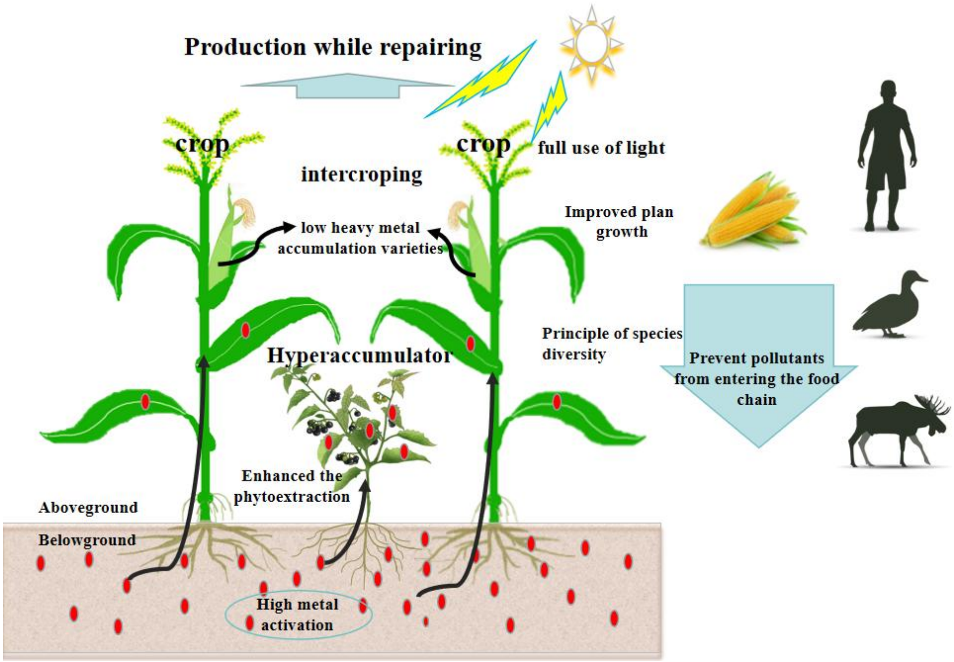

Figure 1. *Sustainable and safe utilization of contaminated farmland soil*

It is generally believed that crops with low accumulation of heavy metals should have the following characteristics (Du et al., 2017): the accumulation of heavy metals in the roots and ground parts of the crop is very low or at least the edible part is lower than the relevant standards; the crop has good tolerance to heavy metals, and can grow normally in high heavy metal-contaminated soil without significant decrease in biomass. The ratio of the total concentration of Cd in plant tissue to the total concentration of Cd in soil (bioaccumulation factors, BF) and the ratio of the total concentration of Cd in the aboveground part to the total concentration of the element in the root tissue (translocation factors, TF) are less than 1.0. As one of the widely cultivated crops in China, maize has the characteristics of large biomass, short growth cycle, and low enrichment ability of heavy metals in grains. The biomass of non-edible parts of maize is large and the accumulation of heavy metals is higher than that of edible parts. Therefore, it is of great potential to screen out the maize varieties with low heavy metal accumulation in edible parts and high heavy metal content in other parts for 'production

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while repairing' of contaminated soil. Some researchers screened different Cd low accumulation maize varieties (*Table 1*).

A field experiment was conducted to investigate the accumulation of heavy metals (Pb and Cd), in various maize varieties in the vicinity of lead and zinc smelting enterprises. The study revealed that several maize varieties not only thrived in soil contaminated with heavy metals but also exhibited a low capacity to accumulate Pb and Cd. Consequently, these varieties can be recommended for local cultivation to safeguard the food safety of crops (Zeng et al., 2024). These varieties can be directly planted in moderately and lightly heavy metal-contaminated soil, and the accumulation of heavy metals in the edible part is low, which meets the national food safety standards. At the same time, maize varieties with low stems and leaves and high biomass can be used as good raw materials for biochar preparation, achieve better economic value, reduce the amount of agricultural waste, improve the comprehensive utilization rate of agricultural waste, and have good environmental benefits. Zhang et al. (2022) was carried out with 50 varieties of maize in a field experiment. The varieties with high, medium and low accumulation of Cd in grains were screened by cluster analysis. And found that the Cd content in the grains of most varieties was higher than the limit value of Cd 0.1 mg/kg in the National Standard for Food Safety-Limits of Pollutants in Food (GB2762-2022) due to the serious Cd pollution in the test site. However, the grain Cd content of all varieties did not exceed the 1.0 mg/kg limit of Cd in the Hygienical Standard for Feeds (GB13078-2017). Therefore, the grain can be used as animal feed at the harvest stage, and other parts can be recycled as repair parts to achieve the purpose of production and repair at the same time. Deng et al. (2019) has found that Huacainuo 3 and Guanghongnuo 8 can be used as Cd-enriched maize varieties and cannot be used as food or feed. And Zhongnuo 1 can be used as a low Cd accumulation maize variety and can be used as food or feed through field experiments. Chai et al. (2022) used 50 local grown maize varieties in Qixingguan District of Bijie City as materials to screening of safe maize varieties of heavy metals in cadmium (0.48, 1.61 mg/kg)-contaminated farmland. The study found that all 50 maize varieties can be planted as feed. Except Xinzhongyu 801, Jinduyu 2, Jinduyu 808, Kangnongyu 109, Tongyu 3, Yudan 7 and Jinxiang 369 could not be cultivated as food grain, the other maize varieties can be cultivated as food grain. Fan et al. (2023) analyzed the characteristics of cadmium absorption, transport and accumulation at seedling stage of 24 maize varieties and the correlation between cadmium with other nutrient elements through nutrient solution culture experiments. It was found that Weike 702 and Denghai 652 were dominant maize varieties with low accumulation of cadmium and easy accumulation of nutrient elements. Wang et al. (2016) studied the transport and accumulation characteristics of Cd in 19 maize varieties through field plot experiments, and found that Yudan 19, Zhengda 999 and Xianyu 508 had less Cd accumulation in grains which was safe for food and human health. The distribution of Cd in maize is generally stalk and leaf > root > grain.

Cultivating and consuming vegetables on soils contaminated by metals in Havana poses significant health risks, which underscores the need for public policies that ensure both the sustainability of urban agriculture and food security (Alfaro et al., 2021). The presence of industrial waste contaminants in food production areas can gravely imperil the health of both farmers and consumers. To address these issues, it is essential to implement strategies that mitigate the impact of heavy metals on soil and crops, as well as to establish food safety measures that protect public health. In recent years, on the

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basis of population genomics, Yan et al. (2023) have established a large data set of phenotype-genotype of Cd accumulation in maize grains by using phenotypic group and genome-wide association analysis. The phenotypic prediction of 100 maize inbred lines showed that the prediction accuracy was 0.81. It laid an important foundation for the establishment of low-cadmium intelligent breeding platform for crops, and provided a new tool for accelerating the early warning of cadmium pollution risk and breeding of low-cadmium varieties. In summary, taking advantage of the huge differences in the absorption of heavy metals by different crop varieties, a large number of heavy metals entering the food chain can be effectively reduced through the adjustment planting structure and variety breeding, thus ensuring human health.

Table 1. *Screening of varieties with low Cd accumulation in different maize varieties*

No.	Screening conditions	Low Cd accumulation maize varieties	Seed Cd content (mg/kg)	BF	TF	References
1	Field experiment	Hongdan 6, Hongyu 1, Yunyou 78, Pingdan 2, Pingdan 2	0.06-0.31	0.096-0.241	<1	Du et al., 2017
2	Field experiment	Xindan 58, Meijia 303, Jinnongke 828, Suyu 29, Dedan 123, MC121, Aoyu 503, Fanyu 298, Nongda 372, Jinqiu 119, Xianda 601, Xuntian 1102, Jinnongke 728, Hemao 808, Jinyu 1233, Huaiyu 23, Yufeng 303, Deli 666, Dedan 5, Jiaxi 100, Bangboshi 76, Zhongkeyu 505, Shaodan 08, Longping 206, Liyu 35, Liyu37, Fengdu 191, Yudan 9953, Wanyu 708	0.09-0.85	<1	0.08-1.31	Zhang et al., 2022
3	Pot experiment	Dongdan 16, Dongdan 60, Shenhe 118, Fuyou 9	0.004-0.081	0.004-0.081	0.03-0.44	Xin et al., 2017
4	Field experiment	Zhongnuo 1	0.07	0.032	<0.1	Deng et al., 2019
5	Field experiment	Yudan19, Zhengda999, Xianyu508	0.1393-0.1833	0.09-0.2	0.29-0.71	Wang et al., 2016
6	Field experiment	Yufengyu 88, Fuke 7, Datian 1	0.05-0.09	0.03-0.06	0.04-0.08	Li et al., 2022

Bioaccumulation factors (BF), the ratio of the total concentration of Cd in plant tissue to the total concentration of Cd in soil; Translocation factors (TF), the ratio of the total concentration of Cd in the aboveground part to the total concentration of the element in the root tissue

Effects of intercropping on plant growth

Intercropping is a traditional farming system that can increase crop diversity, enhance the function of agricultural ecosystems, and reduce chemical inputs. Intercropping systems have many advantages such as improving environmental resource utilization efficiency and productivity, and reducing pests and weeds (Yang et al., 2021a; Xu et al., 2021). At present, intercropping has attracted much attention due to its importance in sustainable agriculture. Studies have pointed out that although farmers can theoretically increase planting density to increase yield, factors such as increased temperature, water resource limitations, reduced sunshine, and lodging risks limit farmers' planting density decisions. The implementation of optimal planting density management can approximately double the current corn yield (Luo et al., 2023). The crop categories and varieties have a dual role in promoting and inhibiting the growth and development of hyperaccumulators. The reason for this phenomenon may be caused by the fact that crops and hyperaccumulators have the same needs or utilization of resources, forming interspecific competition, while crops have stronger competitiveness and can make more use of nitrogen, phosphorus and organic matter in soil, etc. Hyperaccumulators are at a disadvantage in competition, resulting in a significant

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decrease in biomass (Hu et al., 2019). The intercropping of lead hyperaccumulator *Vitex negundo* with *Vicia faba* L. and maize, and the intercropping of *Sedum plumbizincicola* and maize have increased the biomass of hyperaccumulators in different extent, thus promoting the improvement of remediation efficiency (Chen et al., 2019).

The intercropping system affects the enrichment and transport of heavy metals by hyperaccumulators. By increasing the bioavailability of heavy metals in the soil to promote the absorption of the underground part of the hyperaccumulator and the accumulation of the aboveground part. The intercropping of *Sonchus asper* L. Hill and maize that increased the Cd content in the *S. asper* L. Hill (Qin et al., 2013). Root is the main part of absorbing heavy metals in soil. And root status that such as root length, root surface area, root volume, lateral root number and root activity were all affects the ability of hyperaccumulators to absorb nutrients and heavy metals in soil. Compared with monoculture, the aboveground and root biomass, root length, root diameter and root volume of intercropping were significantly increased (Qin et al., 2020). Increasing the root development could help hyperaccumulators to absorb more nutrients and increase the accumulation of heavy metals.

In the intercropping system, the biomass of vegetable crops in both underground and above-ground parts increased, which significantly increased the yield of crops and thus increased the economic value. The intercropping of *Solanum nigrum* and maize, the grain yield of intercropping maize was significantly higher than that of monoculture (Yan et al., 2020). The plant height difference of intercropping plants can change the light distribution in the canopy and increase the utilization efficiency of light energy, thereby increasing the photosynthetic capacity and dry matter accumulation of leaves and distributing them to grains, thereby increasing the yield of maize (Li et al., 2020). Intercropping of maize and *S. nigrum* can increase the available Cd content in the rhizosphere soil of *S. nigrum*, but decrease the available Cd content in the rhizosphere soil of maize. So as to promote the absorption and enrichment of Cd by *S. nigrum*, and reduce the absorption of Cd by maize, thereby alleviating the absorption and enrichment of Cd by intercropping maize, and ensuring the stable yield and food safety of maize. Therefore, the intercropping of *S. nigrum* and maize is an ideal repair germplasm resource for repairing Cd-contaminated soil (Yan et al., 2020). In the intercropping system of *S. nigrum* and maize (Huo et al., 2019), the enrichment coefficient of maize decreased by 68.5%, the transport coefficient of maize decreased by 24.2%, and the heavy metal content in the edible part (grain) decreased significantly compared with maize monoculture. It also shows that the intercropping system can effectively reduce the content of heavy metals in the soil, and the quality of the harvested crops meets the national limit standard of pollutants in related foods. A biotechnology-centered remediation technology framework can greatly simplify the field practice of safe agriculture and be accepted by governments and farmers (Li, 2019). At present, the treatment methods mainly include compression landfill method, composting method, incineration method and so on. Incineration can effectively reduce the volume of plants that accumulate heavy metals, but the process is not mature enough. How to treat incineration residues has not been effectively solved, and the pollution caused by leachate produced in composting and compressed landfill is also difficult to be effectively controlled (Li et al., 2018). The principle of hyperaccumulator remediation of heavy metal-contaminated soil is to use their roots to selectively absorb heavy metals and transport them to the above-ground part. The total amount of heavy metals removed by the soil is the product of the metal content of the plant tissue multiplied by the

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biomass. The aboveground part has a large biomass, which means that the increase of heavy metal content means higher remediation efficiency and better remediation effect. The best intercropping remediation system is to ensure that the Cd content in the edible part of crops is as low as possible while ensuring the increase of crop yield, and to maximize the total extraction of Cd from hyperaccumulator.

Application of intercropping in remediation of heavy metal-contaminated soil

In the face of the common problem of soil heavy metal pollution, optimizing crop planting strategies and rational utilization of crop intercropping have become the focus of phytoremediation research. Intercropping is a widely used agronomic strategy, and many important achievements have been made in the theoretical and practical research of plant intercropping system. Intercropping can make more efficient use of resources, improve land utilization rate and yield stability (Cao et al., 2021; Xu et al., 2021), improve soil fertility, reduce fertilizer application, reduce environmental hazards and increase farmers' income (Ryan, 2021; Li et al., 2021; Feng et al., 2021). In the process of planting hyperaccumulators to remediate the soil, sustainable agro-ecosystem design can be carried out through intercropping with crops without stopping the original crops, and it could be 'production while repairing,' thus improving land use efficiency and generating significant economic benefits (Guo et al., 2021). Intercropping can increase plant diversity and is an important measure to achieve sustainable agricultural development. Reasonable optimization of planting pattern can increase yield and efficiency of planting system (Sun et al., 2020).

The rate of publications on maize and contaminated soil was increased greatly from 2015 to 2021 (*Fig. 2*). The distribution of the 1954 publications by Web of Science category, was 93.38% in Environmental Science Ecology. Previous studies have shown that intercropping can promote the growth of plants in contaminated soil and improve their resistance. Maize roots have good morphological plasticity, and the morphological and physiological responses of maize roots have a significant synergistic effect on improving nutrient use efficiency and yield (Jing et al., 2022). Intercropping can improve soil micro-ecological environment and plant productivity by improving soil microbial community and soil physical and chemical properties (Li et al., 2023; Peng et al., 2022). Intercropping for 'production while repairing' is affected by factors such as plant species, planting patterns, and soil types (Ma et al., 2021; Ng et al., 2023; Qin et al., 2022; Cao et al., 2021, 2020; Yang et al., 2021b). For example, the intercropping of *Sedum alfredii* and *Pinellia ternata* can increase the yield of *Pinellia ternata* and reduce the accumulation of Cd (Ng et al., 2023). The intercropping of *Astragalus sinicus* L. and *Pennisetum purpureum* Schum can reduce the accumulation of Cd in the above ground part of the *Pennisetum purpureum* Schum, so it can be safely used as feed production (Qin et al., 2022). The intercropping of *S. allfredii* and *Brassica napus* L. in different soil types significantly improved the extraction efficiency of Cd by the two plants (Cao et al., 2021). The intercropping of *S. allfredii* with *B. napus* L. and *Brassica juncea* L. promoted the absorption and enrichment of Cd in rape and improved the remediation efficiency (Cao et al., 2020). Although the intercropping of *S. alfredii* and *Brassica oleracea* increased the Cd content in the edible part of *B. oleracea*, but it has been assessed that the consumption of food produced by intercropping does not pose a health risk (Ma et al., 2021). The intercropping mode of *Solanum nigrum* and maize can not only ensure the stable yield of maize, but also significantly improve the repair

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efficiency (Yan et al., 2020). Under monocropping or intercropping, the main part of maize absorbing Cd are all in the roots, but intercropping significantly reduced the transport coefficient of maize (the ratio of heavy metal content in the above-ground part of the plant to the underground part), and reduced the ability of maize to transport heavy metals to the aboveground part, so the Cd content in the grain decreased. However, the effectiveness of intercropping methods may be limited by crop varieties and soil types. For example, some hyperaccumulators may perform better in specific soil types and may grow poorly in other soils. The cadmium absorbed by maize was mainly stored in the roots, and the intercropping significantly reduced the transport coefficient of maize and the transport capacity of heavy metals to the aboveground part (Zhang et al., 2022). This suggests that intercropping methods may affect the bioavailability of heavy metals by changing plant growth characteristics and root exudates, but this effect may vary depending on crop varieties and soil conditions.

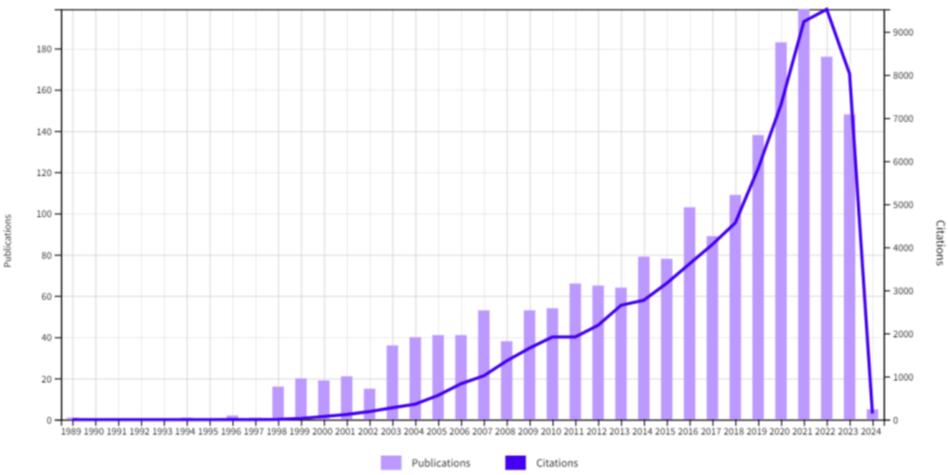

Figure 2. *Times cited and publications over time*

While hyperaccumulators accumulate a large amount of heavy metals by themselves, intercropping with appropriate crops can improve their remediation efficiency to a certain extent, and also ensure the safe production of agricultural products. Therefore, planting hyperaccumulators together with low accumulative crop varieties can be used as a strategy for the safe production in light and moderate contaminated soils (Wan et al., 2020; Yang et al., 2021b; Ma et al., 2021). However, this requires that the heavy metal content in the edible parts of the selected low accumulation crop varieties must meet the requirements of the national standard "National Standard for Food Safety-Limits of Pollutants in Food" (GB2762-2022), which can not only ensure the food safety of agricultural products, but also meet the needs of agricultural production, so as to achieve the purpose of 'production while repairing' of contaminated soil. Phytoremediation technology has produced a large amount of hyperaccumulating plant biomass, and the safe treatment of these biomass is an important issue in the field of phytoremediation (Lei et al., 2021). In order to reduce, recycle and harmlessly treat these hyperaccumulators, a variety of treatment technologies have been extensively studied in recent years, including incineration, composting and landfill. Considering the post-harvest of hyperaccumulators and the appropriate treatment of heavy metal-loaded biomass, thermochemical conversion methods, such as incineration, pyrolysis and

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gasification, can be used to convert biomass into energy, syngas, biofuels, biochar or ash. These methods can not only avoid secondary pollution, but also improve the practicability and economy of phytoremediation technology.

Conclusions and prospects

Intercropping represents a sophisticated agricultural practice that combines intensive cultivation with ecological benefits. The integration of hyperaccumulators with traditional crops not only regulates their growth and development but also enhances the hyperaccumulators' resilience to heavy metals, boosts their metal absorption and enrichment capabilities, and concurrently increases the yield and quality of certain crops. This approach holds significant potential for the remediation of heavy metal-contaminated soils. Looking ahead, future research should focus on the following areas to advance the practical application of intercropping in phytoremediation:

(1) Screening and cultivation of native enrichment plants: It is essential to select and cultivate native enrichment plants that are well-adapted to local conditions, leveraging both traditional and modern breeding techniques to develop new varieties with high biomass, short growth cycles, and superior remediation efficiency. Research should also concentrate on the suitable species range and tolerance levels of selected hyperaccumulators to various heavy metals, creating a comprehensive national database for data sharing and enhancing the application of hyperaccumulators in contaminated soils.

(2) Development of efficient intercropping systems: The remediation efficiency of heavy metal-contaminated soils can be significantly influenced by the characteristics of hyperaccumulators, including their tolerance, enrichment, and transport abilities, as well as root growth characteristics and environmental factors. The selection of enriched plants with large biomass, strong adaptability, and farmer acceptance is crucial. Agricultural practices should be optimized to integrate intercropping, interplanting, and crop rotation strategies that maximize yield while removing soil heavy metals. Additionally, the development of low-accumulation crop varieties and cultivation techniques for contaminated soils is necessary to ensure safe and high-yield agriculture.

(3) Mechanisms affecting heavy metal uptake and accumulation: While intercropping can both promote and inhibit the growth of hyperaccumulators and crops, current research is primarily focused on growth status, enrichment capacity, and physiological and biochemical responses. There is a need for deeper investigation into the molecular biological mechanisms underlying these processes to fully understand the impact of intercropping on heavy metal absorption and accumulation.

(4) Innovative post-remediation disposal technologies: The safe disposal of plant material after phytoremediation is a critical challenge. New treatment technologies must be developed to minimize secondary pollution and adhere to the principles of reduction, reuse, and recycling. This includes assessing the economic feasibility and environmental impact of post-harvest disposal methods, which is an urgent issue that requires attention.

In conclusion, the intercropping of hyperaccumulators with crops offers a sustainable approach that aligns with both agricultural productivity and environmental restoration goals. Future research directions should aim to refine these practices to improve their effectiveness and practicality, ensuring that phytoremediation can be implemented as a viable solution for heavy metal-contaminated soils while maintaining agricultural productivity.

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