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Research Progress on Safe Utilization and Remediation Technologies of Cadmium-Contaminated Farmland Soil

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Abstract

Soil cadmium (Cd) pollution has become a prominent environmental problem restricting the sustainable development of agriculture and food security in China. Under the background of scarce cultivated land resources, the safe utilization technologies such as in situ immobilization, screening of low-accumulation crops and combined regulation are adopted for moderately and lightly Cd-contaminated farmland, which is the core path to realize "production while remediation". This paper systematically sorts out the current situation, sources, ecological and health hazards of Cd pollution in farmland soils in China, reviews the principles, characteristics and application progress of four remediation technologies including physical, chemical, biological and agronomic regulation, focuses on the research results of immobilizer development, screening of low-Cd-accumulation wheat varieties and their combined remediation, analyzes the shortcomings in the research of Cd-contaminated alkaline farmland in northern China, and takes Jiaozuo area as an example to illustrate the regional research status. Finally, it prospects the construction of efficient green immobilization materials, precise matching of varieties and immobilizers, long-term mechanism in field and regional technical system, aiming to provide theoretical reference for the safe utilization and scientific management of Cd-contaminated farmland.

Keywords

Farmland Soil; Cadmium Pollution; In Situ Immobilization; Low-Accumulation Wheat; Combined Remediation; Safe Utilization.

1. Introduction

With the rapid development of industrialization, urbanization and agricultural intensification, heavy metals have been continuously imported into farmland through industrial waste gas, wastewater, residue, sewage irrigation, fertilizer input, mining and smelting, resulting in soil quality degradation and excessive heavy metals in agricultural products, which further threaten human health through the food chain [1-3]. According to the *National Soil Pollution Survey Bulletin* issued in 2014, the over-standard rate of heavy metals in cultivated land soils in China reached 19.4%, among which Cd ranked first with an over-standard rate of 7.0%, becoming the most important heavy metal pollutant in farmland [3-5]. Cd is characterized by high toxicity, non-degradability, easy accumulation and strong concealment. It can inhibit photosynthesis and enzyme activity of crops, reduce yield and quality, and accumulate in human body to cause health risks such as kidney injury, osteoporosis and cancer [6,7].

The main wheat-producing areas in China are mostly located in the northern region, and some farmland soils are alkaline. The environmental behavior of Cd is significantly different from that in acidic soils [8]. Constrained by the total amount of cultivated land and food security, large-scale fallow and engineering remediation are difficult to implement. Safe utilization has become the mainstream strategy for the treatment of moderately and lightly contaminated farmland [3,4]. *In situ*

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immobilization can reduce the bioavailability of Cd, and low-accumulation varieties can reduce absorption and accumulation from the crop level. The combination of the two can achieve the synergistic effect of "reducing activity and low absorption", which is suitable for field production [9].

Based on existing research, this paper systematically summarizes the characteristics of Cd pollution in farmland, remediation technologies, variety screening and combined regulation progress, combined with the regional research foundation of Jiaozuo, points out key scientific problems and technical bottlenecks, and provides support for the sustainable utilization of Cd-contaminated farmland in China.

2. Characteristics, Sources and Hazards of Cadmium Pollution in Farmland Soil

2.1 Current Situation of Pollution

Cd pollution in farmland in China presents a distribution pattern of wide coverage, prominent local areas, severe in the south and light in the north, decreasing from southeast to northwest, with concentrated excessive standards in southwest and central-south regions [10,11]. The total area of Cd-contaminated cultivated land in China is about 13,000 hm^2, involving 25 regions in 11 provinces, especially in industrial and mining areas and economically developed areas [12]. Cd pollution is mainly slight and mild, with only 0.5% of severe pollution, but the risk of long-term accumulation continues to increase [13,14].

Northern alkaline soils have high pH and rich carbonate, and Cd mostly exists in stable forms with low proportion of available forms. However, exogenous input can still lead to excessive Cd in wheat grains, highlighting the pressure of regional safe production [15-17].

2.2 Sources of Pollution

Sources of Cd in farmland are divided into natural sources and anthropogenic sources, with anthropogenic sources dominating [18,19].

Natural sources: Released from soil parent materials. The background value of Cd in Chinese soils is 0.097 mg/kg, lower than the global average of 0.35 mg/kg, and some local areas such as Guizhou and Guangxi have high background values [20,21].

Anthropogenic sources: ① Industrial waste gas deposition and wastewater irrigation; ② Long-term application of Cd-containing phosphate fertilizers, which are important input items [22,23]; ③ Untreated sewage irrigation and sludge agricultural use; ④ Leaching and diffusion of tailings from mining and smelting. In the North China Plain, Cd input is dominated by manure (76.6%), irrigation water (9.21%), atmospheric deposition (8.19%) and phosphate fertilizer (6.00%) [24].

2.3 Ecological and Health Hazards

Hazards to crops: Cd inhibits chlorophyll synthesis and antioxidant enzyme activity, destroys photosynthesis and respiration, reduces soluble sugar and protein content, leading to stunted growth, decreased yield and deteriorated quality [12,13,25].

Hazards to human health: Cd is not an essential element for human body. It accumulates through the food chain, damages cardiovascular, immune and reproductive systems, causes emphysema, anemia, kidney injury, osteodynia, and has carcinogenic and teratogenic risks [10,26,27].

3. Research Progress on Remediation Technologies of Cadmium-Contaminated Farmland Soil

3.1 Physical Remediation

Physical remediation includes soil replacement, isolation, electrokinetic remediation, heat treatment, etc., aiming at complete removal or isolation [28]. Soil replacement has stable effect but high cost and destroys soil layer structure; electrokinetic remediation is limited in low-permeability soils; heat

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treatment has high energy consumption and easily causes soil compaction and microbial inactivation. On the whole, physical remediation is suitable for small-area severe pollution and is difficult to popularize in the field [29].

3.2 Chemical Remediation

Chemical remediation focuses on *in situ* immobilization. By adding immobilizers to change Cd forms and reduce bioavailability, it has the advantages of low cost, simple operation and no impact on farming, making it the preferred technology for farmland [25,26].

Inorganic immobilizers: Lime, silicon-calcium materials, phosphorus-containing materials (calcium dihydrogen phosphate, hydroxyapatite), which fix Cd by increasing pH and forming precipitates [30].

Organic immobilizers: Biochar, organic fertilizer, which fix Cd through adsorption and complexation, and have the effect of improving soil [27,28].

Clay minerals: Sepiolite, bentonite, zeolite, with large specific surface area and rich negative charges, stabilize Cd through ion exchange and adsorption [12,23,26,31].

Chemical leaching can completely remove Cd, but it is complex in operation and easy to cause nutrient loss, so it is only suitable for small-scale severe pollution [32].

3.3 Biological Remediation

Bioremediation uses plants, animals and microorganisms to absorb, accumulate and transform heavy metals. It is eco-friendly but has long cycle and low efficiency, suitable for light and moderate pollution [30,33]. Phytoremediation focuses on hyperaccumulative plants; microbial remediation reduces Cd availability through adsorption, precipitation and transformation; compound microbial fertilizer and bacterial manure can reduce available Cd, but large-scale application is still limited [33-35].

3.4 Agronomic Regulation

Agronomic regulation realizes safe utilization through water and fertilizer management, variety substitution and planting mode optimization, with low cost and easy implementation. Flooding can improve Cd solidification effect; organic fertilizer promotes Cd transformation to stable forms; low-accumulation varieties reduce absorption from the source, which is a key measure for safe utilization [20,28].

4. Core Technological Progress in Safe Utilization of Cd-Contaminated Farmland

4.1 Research and Application of Immobilizers

In situ immobilization transforms available Cd into stable forms through adsorption, precipitation, complexation and ion exchange, which is the mainstream technology for moderately and lightly contaminated farmland [21].

Inorganic: Lime, calcium-magnesium-phosphate fertilizer rapidly increase pH with significant effect, but excessive application easily leads to soil compaction [5,26].

Organic: Biochar has both adsorption and improvement effects, eco-friendly and becoming a research hotspot [23,36].

Clay minerals: Sepiolite and bentonite have strong stability and are suitable for long-term remediation [22,36,37].

Compound immobilizers: The combination of inorganic-organic-mineral can achieve synergistic effect, which is the future development direction [4,12].

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4.2 Screening of Low-Cd-Accumulation Crop Varieties

There are significant genotypic differences in Cd absorption among crops. The edible parts of low-accumulation varieties have Cd content lower than the national standard without affecting yield [10,28,36].

Rice: Late rice > early rice, indica rice > japonica rice, hybrid rice > conventional rice, super rice has the strongest accumulation capacity [30,31].

Wheat: The Cd enrichment coefficient of grains varies greatly among different varieties, and low-accumulation varieties such as Jimai 22 and Shimai 26 have been screened [9,33,34].

Vegetables: Leafy vegetables such as spinach and celery accumulate significantly more than solanaceous fruits.

Variety screening is mainly based on field test + grain detection, combined with comprehensive evaluation of agronomic traits and yield, providing variety support for regional safe production.

4.3 Combined Remediation of Immobilizers + Low-Cd-Accumulation Varieties

Single technology is difficult to meet the standard requirements of highly polluted plots. The coordination of immobilizers + low-accumulation varieties can achieve the dual goals of soil activity reduction and crop low absorption, with better effect than single measures.

Field experiments show that combined treatment can reduce Cd in wheat grains by 30%~60%, and the compliance rate is significantly improved [34,38]. Low-accumulation varieties have safety thresholds, and severe pollution areas must be combined with immobilization remediation to ensure food safety [39].

At present, most studies focus on acidic soils in southern China. The research on combined remediation of alkaline farmland in northern China is insufficient, and regional adaptation technologies need to be improved urgently [40].

5. Research Status of Cadmium Pollution in Farmland Soil in Jiaozuo Area

As a major grain-producing area in northern Henan and a coal-resource-based city, Jiaozuo has systematic research on heavy metals in farmland [33,36]. There is complex Cd pollution in farmland around Wuzhi County, Jiaoke Road and coal gangue hills, with high Cd bioavailability [33]. The heavy metal content of crop grains is generally safe, but there is a risk of exceeding the standard locally, and the health risk is at an acceptable level [33].

Existing research mainly focuses on pollution assessment and health risk, and the research on coordinated regulation of immobilization + low-accumulation varieties is still blank. This region is dominated by alkaline farmland. Carrying out field experiments of immobilizers combined with low-Cd wheat can fill the technical gap in northern alkaline regions and provide demonstration for similar areas.

6. Problems and Prospects

6.1 Existing Problems

(1) Immobilization materials: Single materials have insufficient long-term effectiveness, and the compound mechanism and environmental risks are unclear.

(2) Synergistic mechanism: The interaction mechanism of variety-immobilizer-soil lacks systematic analysis and precise matching.

(3) Field verification: There is a large deviation between pot experiment and field results, and long-term positioning monitoring and cost-benefit analysis are missing.

(4) Regional adaptation: Special technologies and procedures for northern alkaline farmland are scarce, limiting large-scale application.

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(5) Fragmented system: Lack of a complete set of solutions of "source control-immobilization remediation-variety substitution-whole-process monitoring".

6.2 Research Prospects

(1) Green and efficient compound immobilizers: Inorganic-organic-mineral composite, taking into account effect, long-term effectiveness, economy and environmental safety.

(2) Precise matching of varieties and immobilizers: Establish a genotype response database and form regional optimal combinations.

(3) Long-term field mechanism: Carry out long-term positioning experiments to reveal the mechanisms of morphological transformation, rhizosphere process and microbial response.

(4) Regional technical system: For northern alkaline soils, build reproducible and popularizable safe utilization procedures.

(5) Intelligent management and control: Combine remote sensing and big data to realize accurate pollution identification, precise application of immobilizers and risk early warning.

7. Conclusion

Safe utilization of Cd-contaminated farmland is an important measure to ensure food security and soil health. *In situ* immobilization can efficiently reduce the bioavailability of Cd, and low-accumulation wheat reduces accumulation from the source. The combination of the two is suitable for field production. Northern alkaline farmland has good remediation potential, and coordinated regulation can unify economic, social and ecological benefits. In the future, we should focus on compound immobilizers, synergistic mechanism, field verification and regional system to provide support for the sustainable utilization of Cd-contaminated farmland in China.

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