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Integrated Strategies for the Improvement of Cultivated Soil Barriers in China: Development and Application of Multifunctional Organic Fertilizers from an Agro-Environmental Perspective

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Abstract

With the continuous improvement of agricultural intensification and high-intensity utilization in my country, cultivated land soil is facing the combined stress of multiple barrier factors, which seriously threatens food security and ecological environment quality. Multifunctional organic fertilizer is gradually becoming an important technical path for the restoration of cultivated land barrier soil due to its resource recycling, eco-friendly and multi-dimensional improvement characteristics. Based on the perspective of agricultural resources and environmental science, this paper systematically sorted out the types and causes of major cultivated land soil barrier factors in my country, and focused on analyzing the research and development mechanism, key technical routes of multifunctional organic fertilizer and its application effect in acidified, salinized, compacted, impoverished and polluted soils. Studies have shown that multifunctional organic fertilizer can significantly improve soil physical and chemical properties, enhance biological activity, and improve cultivated land productivity and ecological functions through technical means such as organic-inorganic composite, functional microbial enhancement, slow-release regulation and pollutant passivation. This paper also discusses the regional adaptation model and environmental benefit evaluation system for its promotion and application, and proposes the optimization path for future research and development and application. The research results provide a theoretical basis and technical support for promoting the improvement of cultivated land quality and the green development of agriculture.

Keywords

Arable Land Quality; Soil Barrier Factors; Multifunctional Organic Fertilizer; Agricultural Waste Resource Utilization.

1. Introduction

My country's per capita arable land resources are tight. While ensuring the 1.8 billion mu arable land red line, it is also necessary to improve the quality of arable land to support high-quality agricultural development. In recent years, due to the superposition of factors such as unreasonable farming systems, excessive fertilization, irrigation imbalance and industrial pollution, a large area of arable land in my country has shown a variety of barrier problems such as acidification, salinization, compaction, impoverishment and pollution. According to the "National Soil Pollution Status Survey Bulletin", the rate of arable land exceeding the standard

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is as high as 19.4%, among which heavy metal pollution is particularly prominent. At the same time, the deterioration of soil physical and chemical structure, the decline of biodiversity and the imbalance of nutrient cycles are also becoming more and more serious[1].

Traditional improvement methods are mainly based on single-factor targeted governance, which is difficult to cope with complex and changeable compound barrier arable land problems. In contrast, multifunctional organic fertilizer, as a new fertilizer product that integrates multiple functions such as nutrient supply, environmental remediation and structural improvement, shows excellent comprehensive improvement potential. Its core concept is to utilize agricultural waste (such as livestock and poultry manure, crop straw, etc.) as resources, and to achieve a win-win situation of coordinated governance of barrier factors and resource recycling through compounding functional microorganisms and inorganic improved materials.

This paper aims to review the current research progress of multifunctional organic fertilizers in barrier factor identification, product design, application technology and environmental effect evaluation from the perspective of agricultural resources and environmental science, analyze the existing problems and development trends, and promote its wide application in improving the quality of cultivated land.

2. Analysis of the Main Soil Barrier Factors of Cultivated Land

2.1. Acidification Problem and its Mechanism

Soil acidification is a critical issue predominantly observed in the southern red soil regions and intensive economic crop belts. The primary causes of acidification include the long-term application of physiologically acidic fertilizers, such as ammonium sulfate and urea, acid rain deposition, strong leaching effects, and the release of root metabolites [2]. These factors lead to a decrease in soil pH, which in turn activates toxic metals like aluminum and manganese. The activation of these metals inhibits the activity of beneficial soil microorganisms interfer andes with nutrient absorption by plant roots. Consequently, soil acidification results in the decline of agricultural product quality and significant fluctuations in crop yields.

The application of physiologically acidic fertilizers contributes to soil acidification through the release of hydrogen ions (H^+) during the nitrification process. For instance, ammonium-based fertilizers, when converted to nitrate by soil bacteria, release H+ ions, thereby lowering the soil pH. Acid rain, which is caused by atmospheric deposition of sulfur dioxide (SO_2) and nitrogen oxides (NO_x), also exacerbates soil acidification. The strong leaching effect in red soil regions, combined with the release of organic acids from root exudates, further intensifies the acidification process.

2.2. Trend of Salinization Expansion

Salinization is a growing problem in the inland irrigation areas of Northwest China, the Bohai Bay region, and facility agriculture areas. The primary mechanisms driving salinization include poor irrigation water quality, inadequate drainage systems, concentrated evaporation, and unbalanced fertilization practices [3]. These factors lead to the accumulation of sodium ions (Na^+) in the soil, which disrupts soil aggregate structure, increases soil pH, and results in a "secondary salinization" effect.

Poor irrigation water quality, often characterized by high salt content, introduces excessive amounts of soluble salts into the soil. Inadequate drainage systems prevent the effective removal of these salts, leading to their accumulation. Concentrated evaporation, especially in arid and semi-arid regions, further increases the salt concentration in the soil surface layer. Unbalanced fertilization practices, such as the over-application of nitrogen and phosphorus fertilizers without proper consideration of soil salt balance, also contribute to salinization.

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2.3. Causes of Compaction

The phenomenon of soil compaction is becoming increasingly common in cultivated land due to several factors. These include the reduced frequency of deep plowing and soil loosening, frequent mechanical compaction, and insufficient input of organic matter [4]. Compacted soils exhibit poor air permeability and a reduced proportion of capillary pores, which are detrimental to root respiration and water penetration. Consequently, the efficiency of fertilizer absorption is significantly affected.

Mechanical compaction, often caused by heavy agricultural machinery, compresses soil particles, reducing pore space and increasing soil density. The lack of deep plowing and soil loosening practices further exacerbates this issue by preventing the restoration of soil porosity. Insufficient organic matter input, which is crucial for maintaining soil structure and aggregate stability, also contributes to soil compaction.

2.4. Current Status of Impoverishment

Soil impoverishment is a significant problem in typical regions such as the Loess Plateau and degraded farmland in the Northeast Black Soil Region. These areas are characterized by low organic matter content and weak water and fertilizer retention capacity [5]. The causes of soil impoverishment include soil erosion, insufficient straw return to the field, and long-term high-intensity harvesting practices.

Soil erosion removes the nutrient-rich topsoil, leading to a decline in soil fertility. Insufficient straw return to the field results in a lack of organic matter replenishment, which is essential for maintaining soil structure and nutrient cycling. Long-term high-intensity harvesting practices, without adequate soil restoration measures, deplete soil nutrients and reduce microbial activity.

2.5. Soil Pollution Trends

Soil pollution is an emerging concern, primarily caused by pesticide residues, heavy metal emissions, and plastic film residues. The proportion of polluted barrier farmland is continuously increasing. Heavy metals such as cadmium (Cd), arsenic (As), and lead (Pb) are highly cumulative and can be easily absorbed by plants, entering the food chain and posing significant risks to food safety.

Pesticide residues can persist in the soil for extended periods, affecting soil microbial communities and plant health. Heavy metals, often introduced through industrial emissions and improper waste disposal, can accumulate in the soil and be absorbed by crops. Plastic film residues, commonly used in agriculture, can break down into microplastics, which further contaminate the soil and affect soil quality.

3. Research and Development Basis and Key Technologies of Multifunctional Organic Fertilizers

3.1. Organic-inorganic Synergistic Formula Design

The development of multifunctional organic fertilizers is based on the synergistic combination of organic and inorganic materials. Organic waste, such as livestock and poultry manure, garden waste, rice husks, and fruit residues, serves as the matrix to provide carbon sources and basic nutrients. Inorganic materials, including lime, gypsum, bentonite, zeolite, and fulvic acid, are incorporated to achieve directional regulation of soil pH, structure, and nutrient availability.

The organic matrix improves soil structure and enhances microbial activity, while inorganic materials provide essential minerals and help regulate soil acidity or alkalinity. For example, lime can neutralize soil acidity, while gypsum can improve soil structure and reduce salinity.

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3.2. Directed Enhancement of Functional Microorganisms

Functional bacteria, such as phosphate-solubilizing bacteria, nitrogen-fixing bacteria, stress-resistant bacteria, and heavy metal-resistant bacteria (e.g., Bacillus subtilis, Pseudomonas spp., Trichoderma spp.), are co-cultivated with organic substrates through anaerobic or aerobic fermentation systems. This process enhances the biological activity and targeted repair capabilities of the organic fertilizers.

Phosphate-solubilizing bacteria can convert insoluble phosphorus compounds into forms available to plants. Nitrogen-fixing bacteria convert atmospheric nitrogen into ammonia, which can be used by plants. Stress-resistant and heavy metal-resistant bacteria help plants tolerate adverse conditions and reduce the toxicity of heavy metals in the soil.

3.3. Integration of Nutrient Slow-Release Technology

Nutrient slow-release technology involves the use of polymer coatings, passivation agent complexation, and mineral embedding to regulate the release rate of nitrogen, phosphorus, potassium, and trace elements. This technology ensures that nutrients are released gradually, matching the fertilizer requirements of crops at different growth stages and reducing the risk of nutrient loss.

Polymer coatings can control the diffusion of nutrients from the fertilizer granules. Passivation agents can temporarily bind nutrients, releasing them slowly over time. Mineral embedding can also slow down the dissolution of nutrients, ensuring their availability over an extended period.

3.4. Pollutant Passivation and Degradation Module

Adding biochar, iron oxide, yellow calcium phosphate, chitosan and other modifiers can promote the adsorption and fixation of pollutants or the transformation of chemical forms; at the same time, using microorganisms to degrade organic pollutants such as PAHs and polychlorinated biphenyls to achieve coordinated pollution control .

4. Application Practice and Effect of Multifunctional Organic Fertilizer in Barrier Soil

4.1. Conditioning of Acidified Cultivated Land

Studies have shown that after applying multifunctional organic fertilizer rich in biochar and lime, the pH of red soil increased from 4.5 to 5.8, and the aluminum saturation decreased by nearly 70%. The buffering capacity of organic matter effectively delayed the re-acidification process.

4.2. Improvement of Saline Soil

Compound organic fertilizer containing gypsum and humic acid can promote the excretion of Na^+ and improve ion balance. Typical test areas show that the EC value decreased by 40%, the SAR decreased by half, and the yield of pepper and wheat increased significantly.

4.3. Reconstruction of Compacted Soil Structure

Organic matter rich in polysaccharides and lignin can promote the recovery of aggregate structure and improve soil porosity and permeability. After application, the proportion of large aggregates increased by more than 2 times, the bulk density decreased by 10-15%, and the root activity increased significantly.

4.4. Improvement of Fertility of Poor Soil

After three years of applying organic fertilizer with high organic matter + functional bacteria on the Loess Plateau, the soil organic matter content increased by 87.5%, biomass carbon

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doubled, nitrogen mineralization rate increased significantly, and crop yield increased by more than 35%.

4.5. Risk Control of Heavy Metal Contaminated Soil

The combination of biochar + heavy metal resistant bacteria can reduce the effective state of Cd by 70%, and the Cd content in vegetables by more than 60%, reaching the national safety limit; at the same time, it enhances soil microbial diversity and rebuilds ecological functions.

5. Regional Promotion Model and Environmental Benefit Evaluation

5.1. Regional Adaptation and Product Customization

Different types of obstacles require targeted product design, such as reuse of Ca sources and stress-resistant bacteria in the saline-alkali areas of Northwest China, and enhanced carbon sources and pH-increasing improvers in the acidified areas of South China. A promotion chain of "soil diagnosis-formula recommendation-agronomic integration" can be constructed to achieve precise application.

5.2. Environmental Performance Evaluation System

Based on life cycle assessment (LCA), multifunctional organic fertilizers can reduce GHG emissions by 30%-50%, nutrient loss by 40%-60%, and significantly increase the resource utilization rate of agricultural waste. Its overall ecological benefits are much higher than those of traditional chemical fertilizers.

6. Conclusion

As a green carrier for the improvement of obstacle cultivated land, multifunctional organic fertilizers have shown good application prospects in alleviating soil acidification, salinization, compaction, barrenness and pollution. Current research and development is developing from multifunctional integration to high adaptability and intelligent formulation. However, its large-scale promotion still faces bottlenecks such as poor field stability of microorganisms, lack of standardization of fertilization systems, and insufficient policy support. In the future, the following directions should be promoted:

(1) Construct a regional barrier soil type database and a formula recommendation model;

(2) Strengthen the research on functional bacteria immobilization, slow-release carriers and low temperature tolerance;

(3) Formulate national or industry standardized production and application technical regulations;

(4) Promote the linkage between financial subsidies for green organic fertilizers and market mechanisms;

In order to achieve a "win-win" situation of improving the quality of cultivated land and sustainable agricultural development in my country.

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