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A Review of the Research and Development and Application of Multifunctional Organic Fertilizers based on the Improvement of Impoverished Soil

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Abstract

With the continuous impact of high-intensity agricultural development and climate change, the cultivated land in some parts of my country has shown a trend of impoverishment, such as low organic matter content, poor soil nutrients, and decreased microbial activity, which seriously restricts the sustainable development of agriculture. Starting from the causes of impoverished soil, this paper systematically sorted out its main characteristics and distribution patterns, and summarized the research progress and application effects of multifunctional organic fertilizers in improving soil fertility, improving soil structure, and enhancing biological activity. The key technical paths of multifunctional organic fertilizers, such as design concepts, raw material selection, functional microbial addition, and nutrient slow release, were analyzed in detail. At the same time, combined with actual application cases in typical regions, the improvement potential and promotion model of different types of impoverished cultivated land were discussed. Finally, the article puts forward the current problems and future development directions, in order to provide theoretical support and technical paths for improving the quality of impoverished cultivated land in my country.

Keywords

Impoverished Soil; Multifunctional Organic Fertilizer; Soil Improvement; Microbial Activity; Sustainable Agricultural Development.

1. Introduction

In recent years, with the continuous increase in global agricultural intensification and the continued increase in resource and environmental pressures, the impoverishment of cultivated land has become a major challenge restricting the sustainable development of agriculture. This phenomenon is particularly prominent in my country, forming typical soil degradation zones represented by the Loess Plateau, the Northwest Arid Region and the Northeast Black Soil Degraded Region [1,2]. According to the latest survey data, the organic matter content of cultivated soil in these regions is generally below the warning line of 1.5%, and in some areas of the Loess Plateau it is even less than 1.0%, far below the critical value required to maintain soil health [3]. This severe lack of organic matter directly leads to a significant reduction in soil nutrient storage capacity, a general decrease in cation exchange capacity (CEC) of 30-50%, and a sharp decline in water and fertilizer retention capacity [4]. More seriously, biological activity indicators such as soil microbial biomass carbon (MBC) and basal respiration intensity (BR) are

40-60% lower than those of healthy soil, and the function of the soil ecosystem is seriously degraded [5]. This multi-dimensional and systematic soil degradation has caused an average reduction of 15-25% in grain crop yields and a significant decline in the quality of agricultural products, directly threatening national food security and sustainable agricultural development [6]. In traditional agricultural production, the phenomenon of over-reliance on chemical fertilizers in pursuit of short-term production targets is very common. Statistics show that my country's fertilizer consumption has surged from 12 million tons in 1980 to 54 million tons in 2020, with the application per unit area reaching more than three times the world average [2]. Although this fertilization model can increase crop yields by 20-30% in the short term, its long-term negative effects are becoming increasingly prominent. Studies have shown that excessive application of chemical fertilizers for 10 consecutive years can lead to a decrease in soil pH by 0.8-1.5 units, a decrease in soil aggregate stability by 40-60%, and a decrease in the microbial diversity index (Shannon index) by 30-50% [7,8]. What is more alarming is that this unsustainable soil management model has formed a vicious cycle of "soil degradation-dependence on increased production-greater degradation", and has caused chain environmental problems such as groundwater nitrate pollution and increased greenhouse gas emissions [5].

Faced with this severe challenge, the development of new organic fertilizer products with multiple functions has become a key breakthrough in solving the problem of soil impoverishment. The research and development of modern multifunctional organic fertilizers has broken through the limitations of traditional organic fertilizers and developed in the direction of systematization, precision and functionality [9]. The new generation of products not only needs to provide comprehensive nutrient supply (including N, P, K and trace elements), but also has to have comprehensive functions such as improving soil biological activity (increasing microbial biomass carbon by 50-100%), improving soil physical structure (increasing porosity by 10-15%), and repairing degraded ecosystems (increasing the number of earthworms by 3-5 times) [10]. In particular, by adding specific functional microorganisms (such as nitrogen-fixing bacteria, phosphate-solubilizing bacteria, etc.) and new improvers (such as biochar), the improvement effect of organic fertilizers can be increased by 30-50% and its sustained action time can be significantly extended [11,12].

At present, the research and development and application of multifunctional organic fertilizers are facing important development opportunities. On the one hand, the development of emerging technologies such as microbiome and nanomaterials has provided strong technical support for product innovation [13]; on the other hand, the national "storing grain in the land" strategy and the "dual carbon" goals have created a favorable policy environment for the large-scale promotion and application of multifunctional organic fertilizers. In the future, establishing a full-chain technical system of "soil diagnosis-product customization-effect evaluation" to achieve precise application of organic fertilizer products will become a key path to solving the problem of soil impoverishment and promoting the green transformation of agriculture [3].

2. Formation Mechanism and Characteristics of Impoverished Soil

2.1. Causes of Formation

The formation of impoverished soil is a complex multi-factor driven process involving the synergy of natural factors and human activities[14]. From the perspective of natural factors, wind erosion and water erosion are the main driving factors. Studies have shown that in the Loess Plateau, the annual soil loss caused by water erosion is as high as 5,000-10,000 tons/square kilometer, resulting in the loss of fertile surface soil at a rate of 0.3-1.0 cm per year[15]. Wind erosion is particularly serious in the arid northwest region, where a single strong wind event can cause erosion of 5-10 cm of soil on the surface[16]. These erosion processes not only directly remove the surface soil rich in organic matter and nutrients, but also destroy the stability of soil structure.

Drought and high temperature are another important natural driving factor. In areas with annual precipitation less than 400 mm, soil microbial activity is severely inhibited, and the decomposition rate of organic matter is 3-5 times faster than the accumulation rate[17]. High temperature (>35°C) accelerates the mineralization of soil organic carbon. Studies have shown that for every 1°C increase in temperature, the soil organic carbon loss rate increases by about 5%[18]. The impact of human factors on soil impoverishment is more complex and far-reaching. Over-cultivation is the primary problem. Mechanized tillage has caused the destruction of soil aggregates to reach 40-60%, and the proportion of large aggregates (>2mm) has been significantly reduced [19]. The phenomenon of not returning straw to the fields is widespread. In my country, about 30% of crop straw is not effectively returned to the fields each year, resulting in insufficient soil organic matter replenishment [20]. The problem of dependence on chemical fertilizers is particularly prominent. In the past 40 years, my country's chemical fertilizer use has increased by 3.5 times, but the proportion of organic fertilizer input has dropped from 70% to less than 20% [21]. This unbalanced fertilization pattern has led to significant changes in the structure of soil microbial communities, a decrease in the bacteria/fungus ratio, and a 30-50% decrease in the abundance of functional microorganisms [22].

2.2. Typical Characteristics

Impoverished soils have a series of typical physical and chemical properties and biological characteristics. In terms of organic matter, the content is generally lower than the critical value of 10 g/kg, and in severely impoverished soils it is even less than 5 g/kg[23]. The carbon-nitrogen ratio (C/N) is seriously imbalanced, with the C/N ratio in most areas dropping below 8:1, far lower than the 12-15:1 of ideal soil[15]. This imbalance directly affects the efficiency of soil nutrient cycling.

The soil structural characteristics are characterized by poor aggregate stability, with the proportion of water-stable aggregates often less than 30%, while healthy soils are usually above 50%[24]. Scanning electron microscopy observations show that impoverished soils have a simple pore structure, with the proportion of macropores (>50μm) reduced by 40-60%, and micropores (<5μm) significantly increased[19]. This structural change leads to an increase in soil bulk density (usually >1.4 g/cm^3) and a deterioration in air permeability and water permeability.

The microbiological characteristics are particularly prominent. Microbial biomass carbon (MBC) is usually less than 150 mg/kg, which is only 30-50% of that in healthy soil[21]. Enzyme activity decreases across the board, with urease, phosphatase and sucrase activities decreasing by 50-70% respectively[20]. High-throughput sequencing analysis shows that the relative abundance of beneficial bacteria such as Actinobacteria and Proteobacteria in impoverished soils decreases by 20-40%, while the proportion of stress-resistant bacteria such as Acidobacteria increases[14].

From the perspective of ecosystem function, impoverished soils show "three lows": low nutrients (available nitrogen <50 mg/kg, available phosphorus <5 mg/kg), low activity (basic respiration intensity <20 mg CO_2/kg/d), and low stability (structural stability index <0.3)[17]. These soils are also often accompanied by secondary salinization (conductivity >1 dS/m) or acidification (pH <5.5), forming a complex degradation[25]. Long-term positioning experiments have shown that the coefficient of fluctuation of crop yield in impoverished soils is as high as 30-40%, much higher than the 10-15% in healthy soils[23].

3. Design Concept and Key Technologies of Multifunctional Organic Fertilizer

3.1. Raw Material Compounding and Functional Positioning

The raw material system of modern multifunctional organic fertilizer adopts the design concept of "organic matrix-functional additive-microbial flora"[26]. The organic matrix mainly comes from the resource utilization of agricultural waste, including livestock and poultry manure (accounting for 40-60%), crop straw (20-30%), fruit and vegetable processing residues (10-20%), etc. These raw materials are treated by high-temperature aerobic composting (55-65°C for 7-10 days) to ensure the inactivation of pathogens and the stabilization of organic matter[27]. The functional additive system contains three key components: (1) mineral modifiers such as bentonite (added at 5-8%) can increase the cation exchange capacity (CEC) by 15-20%; (2) biochar (added at 3-5%) can increase porosity and prolong fertilizer efficiency; (3) trace element chelates (such as EDTA-Zn) ensure the effectiveness of trace nutrients[28]. Through scientific formulation, this composite system can stabilize the organic matter content at 35-45% and control the carbon-nitrogen ratio (C/N) within the ideal range of 20-25:1[29].

3.2. Functional Microbial Enhancement

In view of the low microbial biomass carbon (MBC) of impoverished soil (usually <150 mg/kg), a multi-species synergistic inoculation strategy is adopted[30]. The core functional bacterial community includes: (1) phosphate-dissolving bacteria (such as Pseudomonas fluorescens), which increase the release efficiency of insoluble phosphorus by 50-70% by secreting organic acids such as citric acid and gluconic acid; (2) nitrogen-fixing bacteria (such as Azotobacter chroococcum), which can achieve a nitrogen fixation efficiency of 3.5-4.2 mg N/g sugar in nitrogen-free culture medium; (3) lignin-decomposing bacteria (such as Trichoderma reesei), whose laccase activity reaches 120-150 U/mL, which can accelerate straw humification[31]. The microbial agent uses microencapsulation technology (sodium alginate-chitosan composite carrier) to increase the field colonization rate from the conventional 30% to more than 60%[32]. The inoculum amount is controlled at 10^6-10^7 CFU/g organic fertilizer and cultured with the organic matrix through solid-state fermentation (40-50% moisture, 28-32°C) for 5-7 days to ensure the activity of the bacterial flora[33].

3.3. Nutrient Slow Release and Directional Supply

A three-stage slow release technology system is used: (1) The biochar coating layer (thickness 50-100μm) reduces the initial release rate of urea nitrogen from 70% to 30% through pore barrier effect; (2) Poly-γ-glutamic acid (PGA) complexes potassium ions to increase the utilization rate of potassium from 40% to 65%; (3) Magnesium ammonium phosphate (MAP) precipitation technology converts water-soluble phosphorus into a slow-release state, extending the effective period of phosphorus to 90-120 days[34]. Through the differential release design, the phased supply of nitrogen (30-60 days release period), phosphorus (60-90 days), and potassium (45-75 days) is achieved, and the matching degree with the crop fertilizer requirement is improved by 35-50%[35]. Field trials have shown that this technology increases the utilization rate of nitrogen from 30% to 55% and the utilization rate of phosphorus from 20% to 40%[36].

3.4. Coordinated Regulation of Modifiers

Establish a "chemical-physical-biological" triple regulation system: (1) Chemical modifiers include lime (application rate 1-2 t/ha) to adjust pH, and humic acid (3-5%) to enhance buffering capacity; (2) Physical modifiers include silicon calcium magnesium ore powder (particle size <0.1mm), whose porous structure increases soil water holding capacity by 15-20%; (3) Biostimulants such as seaweed extract (containing 0.1% betaine) can improve crop stress resistance[37]. Through response surface method optimization, when the ratio of the three is 3:2:1, the soil CEC can be increased by 25-30%, water use efficiency can be increased by 20%, and crop yield can be increased by 15-25% [38]. Synchronous monitoring shows that this system can increase the soil microbial diversity index (Shannon) by 0.8-1.2 and enzyme activity by 50-80% [39].

4. Application Effects and Typical Cases

4.1. Soil Improvement in Dry Land of the Loess Plateau

The Loess Plateau is one of the most severely impoverished regions in my country, and its comprehensive governance results are directly related to the implementation of the Yellow River Basin ecological protection and high-quality development strategy. Long-term positioning experiments (2018-2021) conducted in typical areas such as Yan'an, Shaanxi and Qingyang, Gansu showed that the application of multifunctional organic fertilizers rich in organic matter (content ≥ 45%) and complex functional bacteria (including nitrogen-fixing bacteria, phosphate-solubilizing bacteria and biocontrol bacteria) for three consecutive years (application rate 30 t/ha·a) produced significant soil improvement effects [40]. Monitoring data showed that:

(1) Soil organic matter content increased from the baseline value of 8.2±0.5 g/kg to 15.6±1.2 g/kg, with an average annual growth rate of 25.3%, significantly higher than the 12.8% of traditional composting treatment ($p<0.05$);

(2) Microbial biomass carbon (MBC) increased from the initial 156±23 mg/kg to 487±56 mg/kg, an increase of 212%, and the microbial community diversity index (Shannon) increased by 1.8-2.3;

(3) The proportion of soil water-stable aggregates (>0.25 mm) increased from 35% to 58%, and the field water holding capacity increased by 22%;

(4) In terms of crop yield, corn yield increased steadily from 5.8 t/ha to 7.8 t/ha, and potato yield increased from 22.5 t/ha to 30.4 t/ha, with an increase of 35-38% [41]. This technical model increased the agricultural output value of the project area by 4,200 yuan/ha through the synergistic mechanism of "organic matter enhancement, microbial activation, and structural improvement", while reducing fertilizer input by 30%, achieving a win-win situation in ecological and economic benefits[42].

4.2. Restoration of Degraded Black Soil in Northeast China

The black soil region in Northeast China is the most important commercial grain base in my country. However, due to long-term high-intensity utilization, the thickness of the black soil layer in some areas has dropped from 60-80 cm in the early stage of reclamation to 20-30 cm, and the organic matter content has dropped from 8-10% to 2-3%[43]. In typical degraded black soil areas such as Changchun, Jilin and Suihua, Heilongjiang (soil organic matter 2.1-2.8%, bulk density 1.35-1.45 g/cm^3), multifunctional organic fertilizer (application rate 25 t/ha) containing biochar (addition amount 15%) and efficient lignin-degrading bacteria (Trichoderma reesei T-25) was used for restoration, and breakthrough progress was achieved:

(1) Soil physical properties were significantly improved: the proportion of water-stable aggregates > 2 mm increased from 18.3% to 34.7%, soil bulk density decreased by 9-12% (from 1.41±0.05 to 1.28±0.04 g/cm^3), and total porosity increased by 15-18%[44];

(2) Nutrient effectiveness was improved: the contents of available nitrogen, phosphorus and potassium increased by 65%, 80% and 45% respectively, among which the addition of biochar reduced the phosphorus fixation rate by 40%;

(3) Biological activity was enhanced: the basic respiration intensity of the soil increased from 1.2±0.2 mg CO_2/g·d increased to 2.8±0.3 mg CO_2/g·d, and phosphatase activity increased by 2.5 times;

(4) Improved crop quality: The protein content of corn kernels increased from 8.7% to 10.2%, and the fat content of soybeans increased from 18.5% to 20.3%, reaching the standard of high-quality agricultural products[45].

Through five years of continuous monitoring, it was found that this technical model can increase the organic matter of black soil by 0.3-0.5 percentage points per year, and improve the stability of crop yield by 25-30%, providing reliable technical support for the protection of black soil[46].

4.3. Application in the Arid and Barren Areas of Northwest China

The arid areas of Northwest China face the dual challenges of water scarcity (annual precipitation <200 mm) and poor soil (organic matter <10 g/kg). In typical areas such as Turpan in Xinjiang (a major grape-producing area) and Jiuquan in Gansu (a major cotton-producing area), the multifunctional organic fertilizer developed by adding bentonite (8-10%) and slow-release nitrogen fertilizer (coated urea, accounting for 15%) has shown unique advantages [47]:

(1) Significant improvement in water use efficiency: The addition of bentonite increased the soil saturated water holding capacity from 32% to 45%, and the water use efficiency (WUE) increased by 40-45%. In vineyard applications, the yield remained stable when the irrigation water volume was reduced by 30%;

(2) The growth period regulation effect was obvious: the cotton growth period was extended by 12-15 days, and the number of effective bolls increased by 25-30%; the grape color change period was advanced by 7-10 days, and the soluble solids content increased by 2-3°Brix;

(3) The biomass increased significantly: the aboveground biomass (dry weight) of cotton increased from 8.5 t/ha to 11.9 t/ha, and the growth of grape shoots increased by 35-40%;

(4) The economic benefits were significant: the net income of cotton planting increased by 2,800 yuan/ha, and the improved grape quality increased the sales price by 1.5-2.0 yuan/kg[48]. Mechanism studies have shown that the layered structure of bentonite can effectively block vertical water infiltration, and its cation exchange capacity (CEC) reaches 80-100 cmol/kg, significantly improving nutrient retention capacity; and the controlled release characteristics of slow-release nitrogen fertilizers make the nitrogen supply curve match crop demand by more than 75%, which is 25 percentage points higher than conventional fertilization[49]. This technical model has been promoted in 68,000 hectares of arid areas in Northwest China, saving an average of 30% water, 25% fertilizer, and increasing production by 15-20%, providing an innovative solution for the sustainable development of agriculture in arid areas[50].

5. Promotion Model and Challenge Outlook

5.1. Regionalized Formulation and Customized Service

The current promotion and application of multifunctional organic fertilizers faces the prominent problem that "one-size-fits-all" products cannot meet the differentiated needs of regions. To solve this bottleneck, it is urgent to establish a "diagnosis-formulation-service" three-in-one technical system based on soil type identification[51]. The specific implementation paths include:

(1) Establishing a regional soil database: integrating data such as soil physical and chemical properties (pH, organic matter, CEC, etc.), microbial community structure and barrier factors.

Currently, a database of 12 typical ecological zones and more than 5,000 sampling points has been established across the country[52];

(2) Developing an intelligent fertilizer distribution system: using machine learning algorithms (such as random forests and neural networks) to analyze the soil-crop-fertilizer response relationship and realize automatic optimization of the formula. Experiments have shown that customized formulas are 25-30% more efficient than general products[53];

(3) Building an agricultural technology service network: relying on the "enterprise + cooperative + farmer" model, carry out soil testing, formula customization and technical guidance services. In the Shandong pilot area, this model increased the adoption rate of organic fertilizer from 35% to 68%[54].

5.2. Standardization and Industrial Chain Collaboration

The lack of industry standards and the fragmentation of the industrial chain have seriously restricted the industrial development of multifunctional organic fertilizers. Key breakthroughs are needed:

(1) Construction of a quality standard system: Establish core indicators such as the number of viable functional microorganisms ($\geq 10^7$ CFU/g), organic matter content (≥30%), and heavy metal limits. Developed countries such as the European Union have established a complete organic fertilizer standard system (such as EC No 889/2008), which is worth learning from [55];

(2) Establish a full-process traceability system: Apply blockchain technology to achieve full-process quality monitoring from raw material collection, production and processing to field application. Data from pilot enterprises show that this technology has increased the product qualification rate to more than 98% [56];

(3) Improve the industrial coordination mechanism: Promote the establishment of a closed-loop system of "agricultural waste collection-organic fertilizer production-planting application". Through this model, a company in Jiangsu has reduced raw material costs by 30% and increased its product market share by 40% [57].

5.3. Mechanism Research and Technological Innovation

The weakness of basic research is still the key bottleneck restricting product upgrading. Key research directions include:

(1) Organic-inorganic synergistic mechanism: exploring the nutrient slow-release behavior at the interface of organic matter and minerals. The latest synchrotron radiation technology reveals that organic-inorganic complexes can extend the nitrogen release cycle by 2-3 times;

(2) Microbial ecological function expression: using metagenomics to analyze the colonization rules of functional microorganisms. Studies have found that specific rhizosphere signal molecules (such as flavonoids) can increase the survival rate of bacterial colonies by 50%;

(3) Intelligent responsive material development: research and development of pH/temperature responsive coating materials to achieve precise matching of nutrient release and crop needs. Experiments have shown that new materials can increase nitrogen utilization to more than 65%.

6. Conclusion and Prospect

6.1. Comprehensive Benefits of Multifunctional Organic Fertilizer

Based on a large amount of research data and field practice verification, multifunctional organic fertilizer has shown significant systematic advantages in improving barren soil. Its core improvement mechanism is mainly reflected in three dimensions:

(1) Organic matter improvement: Through the scientific combination of high-quality organic raw materials (maturity > 80%), the average annual growth rate of soil organic matter can

reach 0.3-0.5 percentage points, which is significantly higher than the traditional fertilization mode. Long-term positioning experiments have shown that continuous application for 5 years can increase the soil organic carbon pool by 35-50%, and the carbon sequestration potential can reach 1.2-1.8 t CO_2-eq/ha·yr;

(2) Microbial activation: The addition of specific functional bacteria (such as nitrogen-fixing bacteria and phosphate-solubilizing bacteria) can increase soil microbial biomass carbon (MBC) by 2-3 times, enhance enzyme activity by 50-80%, and significantly improve the complexity of the microbial network (average path length shortened by 20%);

(3) Structural improvement: Organic-inorganic synergy increases the proportion of water-stable aggregates (>0.25 mm) by 15-25 percentage points, reduces bulk density by 0.10-0.15 g/cm^3, and increases field water holding capacity by 20-30%.

6.2. Future Development Direction

In order to achieve a fundamental transformation of barren arable land towards high, stable and sustainable production, future research and development should focus on three key areas:

(1) Regional adaptation product innovation: Establish a "three-in-one" product design method based on soil type-crop system-climate characteristics. Focus on developing special formulas for typical ecological zones such as the Northeast Black Soil, Loess Plateau, and Red Soil Hills to increase fertilizer efficiency by another 15-20%;

(2) Smart fertilization technology integration: Combine the Internet of Things and artificial intelligence technologies to develop a soil-crop-fertilizer real-time monitoring and precise control system. Pilot data show that smart fertilization can increase the utilization efficiency of organic fertilizer by 30%, and maintain stable production when the amount is reduced by 15%;

(3) Full life cycle assessment: Construct a comprehensive evaluation system covering indicators such as carbon footprint and ecological service value. Preliminary studies have shown that the environmental cost of multifunctional organic fertilizers over their entire life cycle is 40-50% lower than that of chemical fertilizers, and the ecosystem service value is 2-3 times higher.

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