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Research Progress on Soil Improvement by Microorganisms: A Systematic Review

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Abstract. Microbial soil improvement technology plays a crucial role in global soil remediation and sustainable agricultural development, offering an eco-friendly alternative to chemical amendments. This paper focuses on the core findings of relevant studies, discussing the classification and characteristics of microbial improvers, their mechanisms of action, technological advancements, existing challenges, and future development directions. Starting from several typical functional microorganisms such as nitrogen-fixing bacteria, phosphate-solubilizing fungi and probiotic consortia, it elaborates on their roles in enhancing nutrient cycling by converting inert nutrients to plant-available forms and optimizing soil structure by promoting aggregate formation, while sorting out the application progress of technologies such as metagenomics for microbial community analysis and synthetic biology for tailored strain construction. Research shows that these technologies are becoming increasingly mature, with field trials achieving improved soil fertility and crop yields; however, future studies need to deepen efforts in areas such as the design of functional microorganisms, ecological risk assessment to avoid microbial invasion, and interdisciplinary integration combining agronomy and microbiology to strengthen the synergy between soil health and agricultural development.

Keywords: Microbial Improvers, Soil Function, Mechanism of Action, Review

1. Introduction

As a core component of the Earth's ecosystem, soil serves as a medium connecting the atmosphere, hydrosphere, biosphere, and lithosphere. It plays an indispensable role in safeguarding food security, regulating carbon-nitrogen cycles, and maintaining ecological balance. However, with economic development, soil ecosystems are currently facing unprecedented challenges. According to a report by the Food and Agriculture Organization (FAO), over 30% of global soils have experienced varying degrees of degradation, with issues such as soil fertility decline, salinization, heavy metal pollution, and frequent soil-borne diseases being particularly severe—seriously restricting the sustainable development of agriculture [1].

Microorganisms, with their diverse species, strong metabolic activity, and adaptability to various extreme environments, exhibit significant effects in pollutant degradation and disease prevention. Consequently, microbial soil improvement technology has become a research focus among many scholars in recent years. For instance: Glick et al. [2] proposed the "multifunctional synergy" theory of plant growth-promoting rhizobacteria (PGPR), which was the first to elaborate on how PGPR strains synergistically promote plant growth and soil fertility enhancement through nitrogen fixation, phosphorus solubilization, plant hormone secretion, and pathogen antagonism ; the team led by Bonanomi et al. [3] confirmed, through long-term field experiments, that the structural diversity and functional stability of soil microbial communities contribute to the inhibition of soil-borne diseases. They found that beneficial microbial communities in healthy soils can reduce the incidence of soil-borne diseases by over 40% through competition for nutrients and space, as well as the secretion of antimicrobial substances; the team led by Zhang et al. [4] from China Agricultural University focused on the rhizosphere microecology field, successfully revealing the molecular pathway of rhizosphere microorganisms driving soil phosphorus activation using metagenomic sequencing and molecular biology techniques .

Although microbial soil improvement technology has achieved remarkable results in laboratory research and small-scale applications—for example, some microbial agents can increase crop yields by 15%-20% and soil organic matter content by 10%-15%—many problems remain unresolved in large-scale applications. For example, the colonization efficiency of exogenous microorganisms in complex soil environments is low, and their survival period is short; the number of viable microorganisms of many strains decreases by over 80% within 30 days after being added to the soil. Therefore, this paper integrates the latest global research results on microbial soil improvement technology, comprehensively discussing the classification and characteristics of microbial improvers, their mechanisms of action, technological advancements, existing challenges, and future directions. It aims to provide references for the innovation, optimization, and safe promotion of this technology, facilitating the coordinated advancement of soil health and sustainable agricultural development.

2. Classification and characteristics of microbial improvers

Among bacterial species, Bacillus subtilis and Pseudomonas fluorescens are research hotspots. The iturin secreted by the former can inhibit the vital activities of pathogens, achieving an over 75% prevention effect against tomato root rot [5]; the latter, on the other hand, can effectively control wheat take-all disease by competing for iron elements through siderophores [6].

Fungal species are represented by Arbuscular Mycorrhizal Fungi (AMF). The hyphae of Rhizophagus irregularis can extend into soil pores, increasing the phosphorus absorption efficiency of plants by 40%-60%. Additionally, the Glomalin-Related Soil Protein (GRSP) it secretes can promote the formation of soil aggregates [7].

The humic acid carrier developed by Zhang et al. [4] can double the colonization efficiency of Azotobacter chroococcum in soil while enhancing soil water retention capacity ; the straw-based composite carrier developed by Li et al. [8] has an adsorption capacity of 1×10^{10} CFU/g for Bacillus licheniformis, significantly improving potassium-solubilizing efficiency .

3. Mechanisms of soil improvement by microorganisms

3.1. Research on nutrient cycling

In the nitrogen cycle, Rhizobium leguminosarum forms a root nodule symbiotic system with leguminous plants, and its nitrogen fixation accounts for over 60% of the total global biological nitrogen fixation [9]; Nitrosomonas europaea and Nitrobacter winogradskyi constitute the core functional group for nitrification—the former oxidizes ammonium nitrogen to nitrite nitrogen, while the latter further converts nitrite nitrogen to nitrate nitrogen, synergistically completing the key nutrient form transformation [10]; Professor Tang et al. [4] also discovered that the arbuscular mycorrhizal fungus Rhizophagus irregularis can promote the absorption and metabolism of NH_4^+ by host plants by upregulating the expression of the RiCARI gene in arbuscules. Simultaneously, it regulates the synthesis of antioxidant substances through the RiCPSI gene, strengthening the connection between nitrogen metabolism and stress resistance .

Glick et al. [2] further expanded the role of PGPR in nutrient cycling in their research, discovering that some PGPR strains (such as Pseudomonas putida) can promote the release of insoluble potassium in soil by regulating the composition of plant root exudates. Specifically, these strains can induce plant roots to secrete organic acids such as citric acid and malic acid, which dissolve minerals like potassium feldspar and mica in the soil through chelation—converting ineffective potassium into available potassium that can be absorbed by plants. When applied in low-potassium soils, this can increase the potassium absorption of wheat and corn by 20%-25%. Meanwhile, their research also confirmed that PGPR can form a synergistic effect with rhizobia, enhancing the nitrogen fixation efficiency of Rhizobium leguminosarum and increasing the number of root nodules in leguminous plants by 15%-20%, further improving the soil nutrient cycling network driven by microorganisms.

In the phosphorus cycle, the phytase secreted by Penicillium bilaii can specifically degrade organic phosphorus in soil, while the oxalic acid it produces can dissolve insoluble inorganic phosphorus such as calcium phosphate. These two effects work simultaneously to significantly

increase the level of available phosphorus in soil [11].

3.2. Research on soil structure

Wang et al. [12] discovered that the extracellular polysaccharides (EPS) secreted by Streptomyces coelicolor can enhance the cementation between particles, increasing the proportion of large soil aggregates (>0.25 mm) by 20% and significantly improving soil aeration and water retention capacity . Arbuscular mycorrhizal fungi (AMF) are widely used in structural remediation: the hyphae of Funneliformis mosseae can connect soil particles through a "bridging" effect, enhancing the wind erosion resistance of sandy soil; the polysaccharide substances secreted by silicate bacteria can also increase water-stable soil aggregates by 18% and porosity by 12%, further optimizing soil structure [7].

3.3. Progress in pathogen inhibition

Trichoderma harzianum exerts biocontrol effects through a dual mechanism: on one hand, it secretes chitinase to degrade the cell walls of pathogens; on the other hand, it induces plants to produce Induced Systemic Resistance (ISR), increasing the resistance of tomatoes to gray mold by 4 levels [3]. The surfactin synthesized by Bacillus velezensis can directly damage the cell membranes of pathogens, achieving an 80% control effect against cucumber fusarium wilt. Silicate bacteria can also form a dominant microbial community in the rhizosphere, inhibiting pathogens through competition for nutrients and space, and reducing the disease incidence in continuous tomato cropping fields from 28% to 9% [5].

Building on previous research, Bonanomi et al. [3]further revealed the dynamic regulation mechanism of microbial communities in inhibiting pathogens: when the initial density of soil pathogens is low, beneficial bacteria in the community (such as Trichoderma and Bacillus) mainly degrade the spore walls of pathogens by secreting hydrolases such as chitinase and β-1,3-glucanase, reducing the infection ability of pathogens; when the pathogen density increases, the community activates a "quorum sensing" mechanism, increasing the secretion of antimicrobial peptides and Volatile Organic Compounds (VOCs) by adjusting the proportion of its own metabolites, forming a broad-spectrum antibacterial environment. In addition, their research also found that long-term application of organic fertilizers can enhance the "functional redundancy" of soil microbial communities, improving the long-term inhibition ability against soil-borne diseases and controlling the annual recurrence rate of cucumber fusarium wilt below 5%—providing new theoretical support for the long-term prevention and control of soil-borne pathogens .

4. Recent advancements in technologies and methods

Metagenomic technology facilitates a better understanding of the role of microorganisms. Schloss et al. [13] used 16S rRNA sequencing to confirm that the combined application of organic fertilizers and microbial agents can increase the abundance of Bacillus by 3 times ; Chen et al. [14] assembled 32 salt-tolerant functional genomes from saline-alkaline soils using Metagenome-Assembled Genomes technology .

Effective gene editing of microorganisms can significantly enhance their functional effects. For example, Jiang et al. [15] edited the nitrogen-fixation genes of Klebsiella pneumoniae, increasing nitrogen fixation efficiency by 2.3 times ; Zhang et al. [16] introduced a phosphate transport pathway into Escherichia coli, improving phosphorus-solubilizing ability by 150% .

Lehmann et al. [17] showed that loading Bacillus megaterium on bamboo charcoal can triple the microbial colonization efficiency; at the same time, the phosphorus-solubilizing ability of Bacillus combined with the adsorption property of bamboo charcoal reduces phosphorus loss and promotes microbial metabolic capacity, increasing available phosphorus in soil by 1.2 times—providing a reference for fertility enhancement and chemical fertilizer reduction .

5. Conclusion

As a key technology to address soil degradation and promote green agricultural development, microbial soil improvement technology has achieved significant breakthroughs in its application. However, it still has shortcomings in large-scale and long-term applications. Future efforts by scholars are needed to achieve efficient, safe, and sustainable development.

Among existing challenges, soil heterogeneity is a core limiting factor. Regional differences in soil physical structure (particle composition, porosity), chemical properties (pH value, organic matter content), and biological communities (abundance of native microorganisms) result in extremely low colonization efficiency of exogenous functional microorganisms. Studies have shown that only 10%-20% of commonly used Bacillus subtilis can colonize the rhizosphere after being applied to soil, and the number of viable microorganisms decreases by over 80% after 30 days. Additionally, the introduction of exogenous microorganisms may disrupt the balance of native microbial communities—Van Elsas JD's team found that the introduction of Pseudomonas putida can reduce soil nitrogen cycle function by 15%. Furthermore, long-term domestic monitoring data are lacking, and evaluation standards are incomplete; most ecological risk assessments only remain in the short-term laboratory stage, making it difficult to ensure the safe promotion of the technology. In addition, the production and application of microbial agents lack standardization—there are significant differences in viable bacteria content and carrier types among different products, leading to inconsistent application effects and further hindering the industrialization process.

Future development should focus on three directions: first, developing specific microorganisms based on synthetic biology—using technologies such as CRISPR-Cas12a for multi-gene editing to integrate functions such as nitrogen fixation and phosphorus solubilization, while optimizing functional efficiency through metabolic network modeling. For example, Jiang Y's team increased the nitrogen fixation efficiency of Klebsiella pneumoniae by 2.3 times after editing its nitrogen-fixation genes; second, building a big data intelligent platform—integrating multi-dimensional data and using machine learning to establish a microbial agent effect prediction model.

In summary, microbial soil improvement technology has great potential in addressing soil degradation and promoting sustainable agricultural development. Future efforts need to overcome bottlenecks through technological innovation, data integration, and institutional improvement, realizing the efficient utilization of microbial resources and ecological risk management—ultimately building a green ecological system that synergizes soil health and agricultural development.

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