Crop Microbiome: Modern Biotechnology Postprint Crossing the Translational Tipping Point

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Abstract

Within the microbiome technology framework, crop microbiomes possess a robust research foundation and vast application prospects, currently standing at a critical juncture for translating fundamental research findings into field applications. The field has achieved breakthrough research advances in several directions, including the interrelationships among crops, microbiomes, and soil environments; the impacts of probiotics and their functional genes on crop growth and development; microbiome-mediated enhancement of efficient crop uptake of nitrogen, phosphorus, iron, and other elements; and microbiome-boosted plant innate immunity and resistance to diverse environmental stresses. Developed nations and multinational agribusinesses have sustained increased investments in this area, with mature products derived from crop microbiome research rapidly capturing markets and being successfully deployed in crop cultivation and production. These technologies exhibit tremendous potential for reducing chemical fertilizer and pesticide usage while substantially improving agricultural yield and quality. China confronts significant challenges in sustainable agricultural development, such as the overuse of pesticides and fertilizers, environmental contamination, and severe disease pressures; the advancement of crop microbiomics and associated technologies will furnish powerful technical support for addressing these issues. Consequently, China must urgently adjust its strategies in crop microbiome project planning, talent cultivation, innovation value chain development, and industrialization to foster research and technological progress in crop microbiomes, thereby making major contributions to national food security and food safety.

Full Text

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Crop Microbiome: A Modern Biotechnology Crossing the Translational Threshold*

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Abstract

Within the microbiome technology system, crop microbiomics has established a solid research foundation and holds broad application prospects, positioning it at a critical juncture for translating basic research findings into field applications. The field has achieved breakthrough progress in elucidating the interrelationships among crops, microbiomes, and soil environments; understanding how probiotics and their functional genes influence crop growth and development; enhancing efficient nutrient uptake of nitrogen, phosphorus, and iron; and improving plant innate immunity and resistance to diverse environmental stresses. Developed countries and multinational agricultural corporations have continuously intensified their investments in this domain, with mature products based on crop microbiome research rapidly expanding into markets and successfully applied to crop cultivation and production. These technologies demonstrate tremendous potential for reducing chemical fertilizer and pesticide usage while substantially increasing both crop yield and quality.

China faces major challenges in sustainable agricultural development, including the abuse of pesticides and fertilizers, environmental pollution, and severe disease threats. Crop microbiomics and related technologies will provide powerful technical support for addressing these issues. Therefore, China urgently needs to adjust its project planning, talent cultivation, innovation value chain development, and industrialization efforts in crop microbiome research to promote the advancement of research and technology, thereby making significant contributions to national food security and safety.

Keywords: crop microbiome, green agriculture, nutrient efficiency, disease and pest resistance, industrialization
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1. Concept of the Crop Microbiome and Its Relationship with Agricultural Development

In nature, normally growing crops harbor vast and diverse microbial communities on their surfaces (both aboveground and belowground) and within their tissues. These microbial assemblages are collectively termed the crop microbiome [1]. These microorganisms encode more genes than their host plants and form stable community structures through cooperation and competition, playing crucial roles in crop growth, disease resistance, and stress tolerance. Current understanding of these microbes remains partial, focusing primarily on rhizobia, arbuscular mycorrhizal fungi, and certain pathogens—representing only a small fraction of the crop microbiome. The majority of root and leaf-associated microbes in crops remain largely unknown (Figure 1 [FIGURE:1]) [2]. Furthermore, due to technical limitations, traditional research has mainly investigated interactions between crops and single microbial isolates under laboratory conditions, rarely examining mechanisms of microbiome-host coexistence under natural conditions. Crop microbiome research treats all crop-associated microbes as an integrated whole at the community level, exploring how they affect various crop physiological functions while emphasizing interactions among microbes and between microbial communities and their hosts.

Crop microbiome research is closely related to agricultural development and has become a cutting-edge hotspot in life sciences. In ancient China, farmers employed crop rotation and intercropping to improve soil fertility and prevent diseases. Recent studies indicate that these sound agricultural practices are associated with the dynamic balance of crop microbiomes [3]. Driven by advances in microbiomics, major international agricultural companies such as Monsanto, Chr. Hansen, Bayer CropScience, and Novozymes have prioritized this area in their research and development portfolios, establishing relatively mature industrial chains. According to incomplete statistics, these leading international agricultural companies invested $2 billion in crop microbiome R&D in 2015 alone.

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2. Crop Microbiome Solutions for Modern Agricultural Challenges

As the world' s leading agricultural power, China faces tremendous pressure to increase grain production, ensure food safety, and address excessive chemical inputs, agricultural waste pollution, and severe soil-borne diseases from continuous cropping. The crop microbiome offers novel perspectives and solutions to these challenges. Therefore, we must urgently adjust relevant project and industrial support policies, increase investment, and strive for rapid breakthroughs in this emerging agricultural biotechnology to safeguard national food and food safety.

2.1 Reducing Excessive Chemical Fertilizer Use

To ensure crop yields, China has increased chemical fertilizer usage year by year, yet utilization efficiency remains at only about 30%. Fertilizer abuse severely pollutes the ecosystem and significantly impacts food safety. Current agricultural production primarily relies on breeding new varieties to improve nutrient uptake efficiency, but this approach suffers from long breeding cycles and high costs. Root-associated microbes play important roles in plant uptake of nitrogen (N), phosphorus (P), and other nutrients. Beyond rhizobial nitrogen fixation and mycorrhizal phosphorus acquisition, other root-associated bacteria and fungi also participate in these processes [4,5]. Recently, novel probiotics that facilitate plant iron (Fe) uptake have been discovered. Systematic investigation of crop microbiome functions in nitrogen, phosphorus, iron, and other essential nutrient acquisitions will deepen our understanding of crop nutrition processes, enable discovery of more probiotics, and ultimately improve nutrient use efficiency while reducing chemical fertilizer application.

2.2 Avoiding Pesticide Abuse

China accounts for one-third of global chemical pesticide consumption. Excessive pesticide use affects environmental biodiversity and threatens human health through teratogenic, carcinogenic, and mutagenic effects and impaired reproductive function, with no effective solutions currently available. Pesticide application also readily induces resistance, carries high costs, and damages ecosystems. The microbiome approach offers new solutions: modifying soil microbiomes to increase antagonistic microbes that suppress soil-borne pathogens. Research shows that effective microbial groups in soil biological control are complex, with multiple probiotics establishing intricate relationships with host plants [3]. Our preliminary results demonstrate that plant root probiotic communities can stably promote plant growth in environments containing *Fusarium oxysporum* or *Verticillium dahliae*. Biocontrol research has shifted from using single microbial strains to utilizing entire microbiomes. Therefore, artificial reconstruction and precise transplantation of root microbiomes based on functional understanding can provide innovative solutions to ecological problems caused by pesticide pollution.

2.3 Providing New Solutions for Continuous Cropping Obstacles

China' s arable land area decreases annually, forcing intensive continuous cropping systems that cause severe disease buildup and declining soil fertility. For example, cotton verticillium wilt in Xinjiang' s major cotton-growing regions and soil-borne diseases in *Panax notoginseng* cultivation represent serious diseases arising from continuous cropping, affecting local agricultural sustainability. Current solutions including soil replacement, diseased plant removal, and seed treatment are costly and ineffective. Recent research indicates that the primary cause of continuous cropping diseases is microbiome imbalance in the soil ecosystem. For instance, outbreaks of soybean pathogen *Ralstonia solanacearum* during continuous cropping mainly result from declining densities of probiotic communities dominated by *Pseudomonas* in the root microbiome [3]. Thus, crop microbiome research is crucial for improving soil ecological environments and overcoming continuous cropping obstacles caused by microbiome imbalance.

2.4 Alleviating Agricultural Waste Pollution

Agricultural waste disposal has emerged as a serious environmental challenge in crop production. Agricultural plastics such as mulch films and irrigation systems have made significant contributions to agriculture, forestry, and animal husbandry, yet large amounts of plastic residues accumulate in farmland, forests, and water bodies, forming barrier layers that create "white pollution." This pollution affects crop root access to water and nutrients and restricts crop growth. Recent studies show that soil microbes can efficiently degrade agricultural plastic residues through active enzymes, offering a completely new approach to waste treatment [6,7]. Investigating microbiome synergies during waste recycling processes could enable efficient agricultural waste treatment with low cost and high efficiency.

2.5 Assisting Crop Improvement from a Novel Perspective

Traditional breeding programs that plant large areas with single varieties focusing solely on yield improvement have led to declining stress tolerance and disease resistance, making it difficult to combine high yield with stress resistance. Beneficial microbes can help plants enhance disease resistance and stress tolerance independently of the host genome. If combined with traditional breeding approaches, this could accelerate breeding speed and improve crop yield and quality from an entirely new perspective.

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4. Policy Recommendations for Advancing China' s Crop Microbiome Research

The strategic goal of crop microbiome research development is to use microbiome technology to reduce modern agriculture's heavy dependence on chemical fertilizers, pesticides, and herbicides while substantially increasing crop yield and quality to achieve sustainable agriculture. China faces population pressure, fertilizer and pesticide abuse, and severe agricultural environmental pollution. Achieving these goals has obvious practical significance for overcoming important technical obstacles in China' s agricultural production. Therefore, we propose five policy recommendations.

4.1 Recognizing the Leading Position of Crop Microbiome Research in Modern Life Science

Compared with other microbiome fields, crop microbiome research has distinct characteristics. First, after years of research on soil and crop root microbial flora, ecology, and soil metagenomics, this field has established a solid foundation. Second, with relatively few ethical and industrial barriers in application, the technology's socioeconomic impact is significant, and its outputs and translation speed are very rapid, making it one of the most readily breakthrough-prone fields in the entire microbiome research system. Strategic planning should therefore emphasize research content in this domain. However, current challenges include insufficient research purposefulness, fragmented data collection, and inadequate interdisciplinary collaboration. Future microbiome research 战略布局 must further consolidate research objectives, focusing on solving practical problems in important Chinese crops (rice, wheat, cotton, soybean, etc.) such as continuous cropping obstacles, rampant diseases, fertilizer and pesticide abuse, and declining soil fertility. This will create an innovation value chain where scientific problems originate in the field, solutions are developed in the laboratory, and advanced technologies benefit agriculture.

4.2 Focusing on Important Crops and Emphasizing Resource Collection, Preservation, and Database Construction

China has diverse crop varieties and highly varied agricultural ecological environments with complex conditions. Taking rice as an example, cultivation areas span six major rice zones from Northeast China to Hainan, crossing multiple climate belts, with altitudes ranging from 0–2,600 meters and soil types including red soil, brown soil, black soil, cinnamon soil, and saline-alkali soil, resulting in large variations in yield and quality. These farmland environments contain rich microbiome resources. Therefore, at the national level, China should establish collection, preservation, and analysis systems for microbiome resources from typical farmland habitats and crop rhizospheres of important crops, strengthening basic surveys and scientific analysis of microbial resources to provide research materials for functional microbiomics. Simultaneously, China should enhance big data analysis and database construction for typical farmland ecosystem microbiomes to lay the resource foundation for microbiome collection, evaluation, and screening.

4.3 Emphasizing Functional Microbiomics and Plant-Microbiome Interaction Research

Based on crop microbiome resource collection and evaluation, functional microbiomics and plant-microbiome interaction research represent not only frontier disciplines in life sciences but also key links for generating basic research outcomes and driving biotechnology development and application. Unlike crop-environment interaction research, crop-microbiome interactions involve multiple life processes with complex mutual influences, promotions, and inhibitions. Understanding the biological essence of these interactions is the scientific guarantee for developing microbiome technologies. Future disciplinary planning should further emphasize talent development and project investment in this field, focusing on in-depth analysis of material and information flows—including nutrients, growth regulators, and signaling molecules—in crop-microbiome interactions. This will elucidate the molecular biological and biochemical foundations of biological interactions, providing scientific basis for artificial design or synthesis of "ideal microbiomes."

4.4 Emphasizing Advanced Technology Application and Industrialization

Compared with multinational corporations like Monsanto, Chinese agricultural companies lag significantly in scale and R&D innovation capacity. For instance, Syngenta' s market value approaches $40 billion with nearly $1 billion in annual R&D investment—about one-quarter of the total annual budget of China' s Ministry of Science and Technology or National Natural Science Foundation. In contrast, Longping High-Tech, one of China's leading agricultural technology enterprises, has a market value of only about $3.5 billion with annual R&D investment of approximately 80 million RMB. Under these circumstances, China still relies primarily on government investment for advanced agricultural biotechnology development through 良性 cooperation between public research institutions and companies. To encourage market allocation of resources, industrial policies should support innovative agricultural companies to increase R&D investment in microbiome technology, gradually shifting from a government-led technology development model. Simultaneously, substantive cooperation between industry and academia should be encouraged to create 良性 interaction between practical agricultural problems and basic microbiome research questions, expanding funding sources and promoting rapid field development.

4.5 Cultivating Innovative, Multidisciplinary, and Diversified Talent

Current scientific research demands high-caliber talent. The research process involves plant science, microbiology, genomics, bioinformatics, and other multidisciplinary backgrounds, requiring researchers with interdisciplinary knowledge, rapid learning capabilities, and the ability to prioritize and distinguish critical issues to lead the field forward.

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Figures

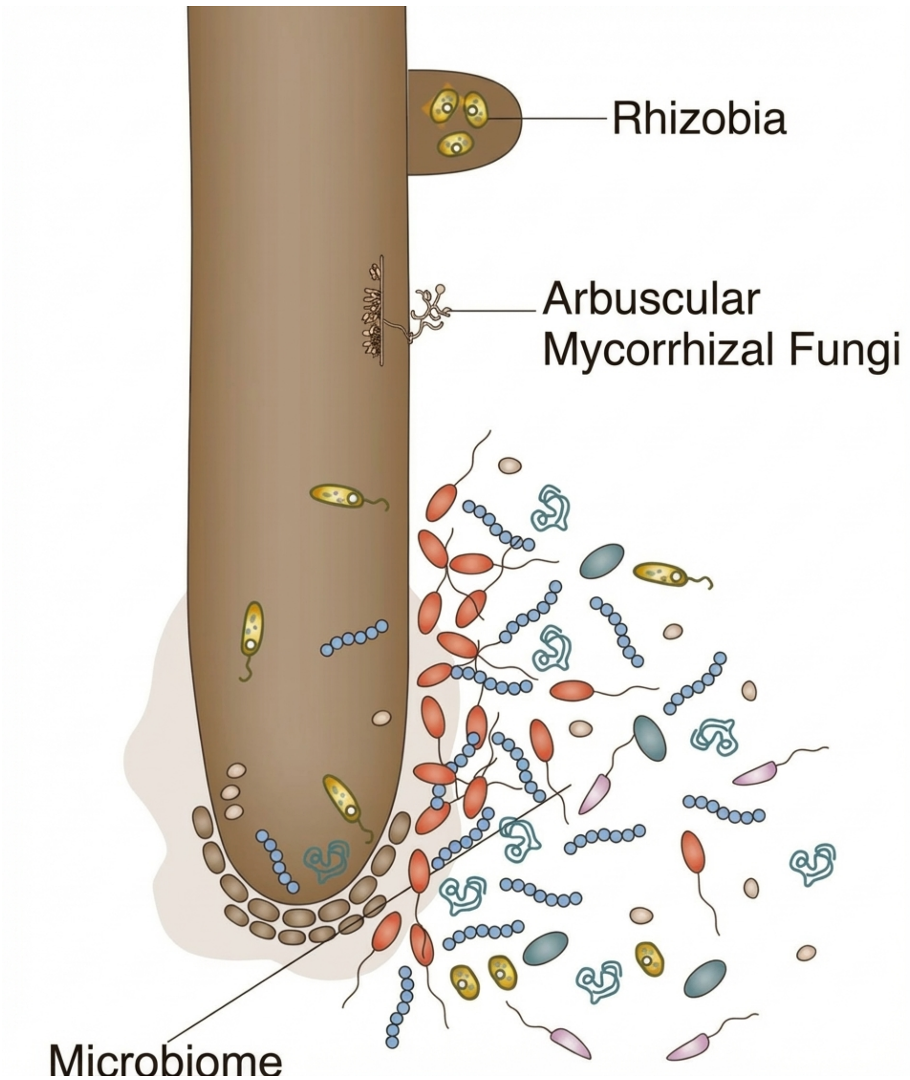

Figure 1: Figure 2