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Communication

Enhancing Soil Health and Plant Growth through Microbial Fertilizers: Mechanisms, Benefits, and Sustainable Agricultural Practices

Xinpei Wei, Benkang Xie, Chu Wan, Renfeng Song, Wanru Zhong, Shuquan Xin * and Kai Song

School of Life Science, Changchun Normal University, Changchun 130032, China;
QX202200176@stu.ccsfu.edu.cn (X.W.); QX202300018@stu.ccsfu.edu.cn (B.X.);
QX202300031@stu.ccsfu.edu.cn (C.W.); QX202200187@stu.ccsfu.edu.cn (R.S.);
QX202100167@stu.ccsfu.edu.cn (W.Z.); songkai@ccsfu.edu.cn (K.S.)
* Correspondence: xinshuquan@ccsfu.edu.cn

Abstract: Soil microorganisms play a crucial role in maintaining the structure and function of soil ecosystems. This study aims to explore the effects of microbial fertilizers on improving soil physicochemical properties and promoting plant growth. The results show that the application of microbial fertilizers significantly increases the richness of soil microorganisms, maintains soil microecological balance, and effectively improves the soil environment. Through various secondary metabolites, proteins, and mucilage secreted by the developing plant root system, microbial fertilizers recruit specific fungal microorganisms. These microorganisms, by binding soil particles with their extracellular polysaccharides and entwining them, fix the soil, enhance the stability of soil aggregates, and ameliorate soil compaction. Moreover, after the application of microbial fertilizers, the enriched soil microbial community not only promotes the plant's absorption and utilization of key elements such as nitrogen (N), phosphorus (P), and potassium (K), thereby increasing fruit yield and quality, but also competes with pathogens and induces systemic resistance in plants, effectively warding off pathogenic invasions. This study highlights the potential and importance of microbial fertilizers in promoting sustainable agricultural development, offering new strategies and perspectives for future agricultural production.

Keywords: microbial fertilizer; soil microbial community; fungal community; bacterial community; soil physicochemical properties

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1. Introduction

The excessive use of chemical fertilizers and long-term cultivation has, to some extent, damaged the soil environment. This condition not only changes the soil's physicochemical characteristics and microbial community structure but also limits the sustainable development of agriculture [1]. The application of microbial fertilizers can increase the diversity of fungal and bacterial communities in the soil and enhance the number of beneficial microorganisms [2]. Specific fungi can form and stabilize soil aggregates, alleviating soil compaction. Soil microorganisms enhance plant disease resistance through mechanisms such as regulating soil pH, increasing soil organic carbon content, and competing with pathogens for survival resources. Moreover, some rhizosphere microorganisms can fix atmospheric nitrogen, unlock phosphorus and potassium in the soil, and provide essential nutrients to plants.

In examining the global landscape of patent origins within the microbial fertilizer sector, the leading five nations in patent production are identified as China, Japan, South Korea, the United States, and Russia. Notably, China emerges as the predominant source of patented innovations in this domain, boasting 9156 patents, which represents 59.8% of the global total. Mycorrhizae stand out as the world's most widely utilized biofertilizers.

By expanding plant root surface area, these symbiotic associations significantly enhance nutrient absorption and utilization. In 2022, mycorrhizae accounted for 36.3% of the biofertilizer market share, translating to a market value of approximately USD 995.3 million and a production volume of 96,600 tons. Rhizobia, known for their nitrogen-fixing capabilities, rank as the second most prevalent biofertilizer on a global scale. North America, in particular, represents the largest market for Rhizobia, comprising 24.8% of the biofertilizer market segment in 2022. Both North America and Europe are identified as principal consumers of microbial fertilizers. In the Asia–Pacific region, China and India lead in the utilization of microbial fertilizers. Despite the relatively recent adoption of organic farming practices in these countries, there has been rapid development in this area, with a noticeable increase in organic agricultural land from 2017 to 2021. Consequently, the market demand for microbial fertilizers is anticipated to continue its upward trajectory. Amidst growing calls for sustainable agricultural practices and a greener ecology, the adoption of microbial fertilizers as a means to enhance crop yields and soil health has emerged as a prevailing trend. Accordingly, the market share of microbial fertilizers within the agricultural sector is expected to witness further expansion in the forthcoming years.

A keyword search for “microbial fertilizers” was conducted to analyze the main research countries and the evolution of research directions in this field since the 20th century. As shown in Figure S1A, the early research hotspots focused on the study of microorganisms dominated by nitrogen-fixing bacteria, as well as the study of bacterial fertilizer on plant growth promotion and yield, while in recent years, the research direction has been biased towards growth promotion mechanisms, luminescent bacteria, and plant rhizosphere growth-promoting bacteria.

Over time, the focus gradually shifted towards mechanisms by which microorganisms promote plant growth, bioluminescent bacteria, plant growth-promoting rhizobacteria, biomass, and their impact on soil properties [3–6]. This shows the development and innovation of modern research techniques.

Citespace was used to analyze the cluster of countries, and the node size was used to represent the development of the country’s microbial fertilizer in different years, and the development was reflected by the number of published papers and the level of journals, reflecting the country’s contribution value in the field of microbial fertilizer. As shown in Supplementary Materials Figure S1B, the United States is the country with the largest contribution in the field of microbial fertilizers, followed by China, the United Kingdom, and France. The circle color corresponds to the year, and the total statistics show that in the decades from 2004 to 2024, the United States and China, as important agricultural producers in the world, have had a large demand for microbial fertilizers, and their research contribution is ahead of other countries. Microbial fertilizers promote plant growth in an ecologically sustainable way [7].

In this paper, CiteSpace was used to analyze the keywords and the number of articles published in the English database, and the definition and characteristics of microbial fertilizer, the mechanism of action, and the application of microbial fertilizer were summarized. In this paper, we reviewed the changes in soil microbial community, the increase in beneficial microbial community, the changes in the life activities of beneficial microorganisms after the application of microbial fertilizer, and the effects of microbial activities in soil on improving soil physical and chemical properties, increasing soil nitrogen, phosphorus, and potassium content, inhibiting soil pathogenic bacteria to remediate polluted land, and the promoting effect of microbial fertilizer application on plant growth.

2. Microbial Fertilizers

2.1. Definition of Microbial Fertilizers

Microbial fertilizers, as an advanced green fertilizer, rely on the life processes of microorganisms to provide directly absorbable nutrients to crops, thereby promoting plant growth and yield enhancement. This is of significant importance for driving sustainable agricultural development [2]. Microbial fertilizer is a new type of chemical fertilizer product which contains a large number of microorganisms, and the mechanism of action is to use live microorganisms to proliferate, so as to produce enough nutrients required by soil and crops. Through the metabolic functions of these microbes—namely the secretion of enzymes, organic acids, and antimicrobial compounds—the composition of the soil's microbial community is enriched. This enrichment results in an increased presence of beneficial bacteria, improvements in soil physical and chemical properties, and an augmentation of essential soil nutrients such as nitrogen, phosphorus, and potassium. Collectively, these microbial activities promote plant growth.

As delineated in Table 1, diverse microorganisms incorporated in microbial fertilizers are listed along with their respective functions. Microbial fertilizers crafted from nitrogen-fixing bacteria afford ammonia or nitrate to plants, facilitating absorption and utilization through the bacteria's inherent biological activities [8]. Lactic acid bacteria, recognized for their antifungal properties, are prime candidates for microbial fertilizer production [9]. Fertilizers derived from these bacteria can generate acids and antimicrobial substances to suppress pathogenic bacterial growth in the soil. Moreover, microbial fertilizers produced from fungi are capable of secreting extracellular enzymes and organic acids, thereby decomposing soil organic matter and altering microbial diversity. Additionally, fertilizers formulated with actinomycetes can enhance soil physical structure, increase water stability aggregate formation, reduce soil bulk density, improve aeration, and secrete antibiotics to inhibit harmful microorganisms.

Table 1. Microorganisms commonly found in microbial fertilizers.

Microbial Fertilizer Species	Major Microorganisms	Function
Bacteria fertilizers	*Nitrifying bacteria*, *Azotobacter chroococcum*, *Azospirillam brasilense*, *Klebsiella*	Convert N_2, which cannot be absorbed and utilized by plants, into ammonia or nitrate to promote plant growth
	Bacillus sp.: *Bacillus cereus*, *Bacillus megaterium*, *Bacillus mucilaginosus* et al. Photosynthetic Bacteria: *Rhodopseudomonas capsulate*, *Rhodopseudomonas* sp. et al. *Pseudomonas* sp.: *Klebsiella pneumoniae*, *Pseudomonas aeruginosa* *Chromobacterium: Alcaligenes* sp. et al. *Serratia* sp.: *Serratia marcescens* et al. *Thiobacillus: Acidithiobacillus thiooxidans*, *Thiobacillus thioparus*	Insoluble phosphorus is converted into soluble phosphorus, and some microorganisms can also release extracellular enzymes to dissolve minerals and convert them into inorganic phosphorus to promote plant growth.
	Bacillus edaphicus, *Bacillus mucilaginosus Krassilnikov* et al.	Through dissolution and mineralization, the insoluble potassium in the soil is converted into soluble potassium, which destroys the mineral structure of silicate and increases the content of available potassium in the soil.
	Lactic acid bacteria	Secretion of acids or antibacterial substances inhibits the growth of pathogenic bacteria in the soil, promotes the growth of plant roots, and improves the absorption of nutrients by plants.
Fungal fertilizers	*Mycorrhizal fungi*, *Ascomycota* et al.	It can secrete extracellular enzymes, organic acids, etc., to decompose organic matter in the soil, improve soil structure, and improve soil fertility.
Actinomycete fertilizer	*Streptomyces jingyangensis*, *Streptomyces pactum* et al.	Secrete antibacterial substances, inhibit the growth of harmful microorganisms, decompose organic matter, reduce soil bulk density, and improve soil physical properties.

In the application of bibliometrics, Citespace, as a popular analytical tool in bibliometrics, provides data support for both quantitative and qualitative analyses by showcasing the distribution, research hotspots, and trends within a specific research area [10]. Analysis of publication volume reveals the scientific progress in this field and the developmental trends over time [10]. As shown in Supplementary Materials Figure S2, since 2000, there has been an overall upward trend in the publication volume within the field of microbial fertilizers. Particularly after 2015, the attention to this field has noticeably increased with more research investments, indicating the growing importance of this field. The peak was reached in 2023.

Supplementary Materials Figure S3 demonstrates the relationship between the knowledge frontier and knowledge base at a macro level, revealing the connections between different research themes through a collection of cited and citing journals. This indicates that research related to microbial fertilizers is broad and interdisciplinary, impacting various themes including plant growth, microbial diversity, soil environment, and animal activities.

The application of microbial fertilizers increases the richness of microorganisms in the soil and the number of beneficial microorganisms, playing a vital role in promoting the formation of soil aggregates, improving soil compaction, providing absorbable N, P, K elements to plants, and resisting pathogen infection.

2.2. Mechanism of Action of Microbial Fertilizers

2.2.1. AAC Deamination Enzymatic Probiotics

1-Aminocyclopropane-1-carboxylate (ACC) serves as a critical precursor in ethylene synthesis, a process intimately linked to the plant stress response [11]. Under stress conditions, plants escalate ACC production, leading to heightened ethylene levels that adversely affect plant growth. The enzyme ACC deaminase plays a pivotal role in mitigating this stress response by catalyzing the decomposition of ACC into butyruvate and ammonia. This reaction effectively lowers ethylene concentrations under stress, thus alleviating its inhibitory effects on plant growth [12]. In the plant rhizosphere, where root growth promotion is essential, the metabolic pathway involving Met (methionine) and ACC outlines the synthesis and impact of ethylene on plant roots. Methionine is converted to S-adenosylmethionine (SAM) by the action of SAM synthetase. Subsequently, ACC synthase catalyzes the transformation of SAM to ACC, which is then converted to ethylene by ACC oxidase. The excess production of ethylene restricts root growth. However, the presence of ACC deaminase allows for the cleavage of ACC into ammonia and α-butyruvic acid. This process not only provides essential carbon and nitrogen sources for microbial growth but also reduces ACC accumulation, decreases ethylene levels in plants, and fosters root elongation (as depicted in Figure 1). Highlighting the practical implications of this biological mechanism, Anumita Sarkar et al. [13] identified strain P23 as a salt-tolerant Enterobacter species harboring ACC deaminase, demonstrating its potential in enhancing plant stress tolerance. Further, Subhan et al. [14] reported on the screening of four drought-tolerant probiotic bacteria possessing ACC deaminase. Their findings revealed that the application of these probiotic bacteria markedly improved maize yield under drought conditions. Additionally, significant enhancements were observed in the photosynthetic rate, stomatal conductance, and the concentrations of chlorophyll A, total chlorophyll, and carotenoids in maize plants.

2.2.2. Produces Plant Hormones and Promotes Plant Growth

Plant hormones, though not directly part of plant tissues and organs, act as small molecular compounds that regulate physiological and biochemical activities in plants, significantly promoting crop growth and development. Rhizosphere microorganisms play a pivotal role in the modulation and production of plant hormones, contributing significantly to plant growth and development. Auxin, gibberellin, cytokinin, ethylene, and abscisic acid (ABA) represent the quintet of primary plant hormones synthesized endogenously by plants, each harboring beneficial impacts on various aspects of plant physiology. Indole-3-

acetic acid (IAA), a type of auxin and a carboxylic acid, is predominantly synthesized from tryptophan. It facilitates plant growth by enhancing cell division, elongation, and differentiation, thereby altering xylem and root development. This modification crucially influences the plant's nutritional uptake and overall development. Bacterial IAA, for instance, is known to increase the surface area and length of plant roots, significantly improving the plant's nutrient absorption capacity [15]. Certain microbial strains, such as *Azotobacter* spp., *Rhizobium* spp., *Pantoea agglomerans*, and *Rhodospirillum rubrum*, have been identified to secrete cytokinin [15]. This hormone is essential for promoting cytokinesis, leading to the differentiation and growth of various plant tissues. Similarly, gibberellin, a diterpenoid compound, is influential in stimulating stem elongation, thereby facilitating plant growth. Ethylene, another crucial plant hormone, serves multiple roles in plant development and stress responses. It aids in root hair formation, seed germination, fruit ripening, leaf abscission, and coping with biotic and abiotic stresses, although it can also inhibit root elongation [15]. The synthesis and regulation of these hormones by rhizosphere microorganisms underscore the intricate relationships within the plant microbiome, highlighting their essential role in supporting plant health and productivity. The interaction between soil microorganisms and plant roots not only facilitates the absorption of essential nutrients by plants but also prevents the accumulation of toxic compounds [16]. Bonartsev et al. [17] discovered that *Azotobacter chroococcum* could regulate plant growth by producing cytokinins. Research by Yasar et al. [18] suggests that certain microorganisms in microbial fertilizers, such as *Bacillus subtilis*, *Bacillus cereus*, and *Bacillus megaterium*, may stimulate root and root system growth in kiwifruit by producing indole-3-acetic acid (IAA). Experiments have shown that *Bacillus subtilis* RC03, *Bacillus simplex* RC19, and *Comamonas testosteroni* RC41 significantly increased rooting rates in kiwifruit stem cuttings by producing more IAA.

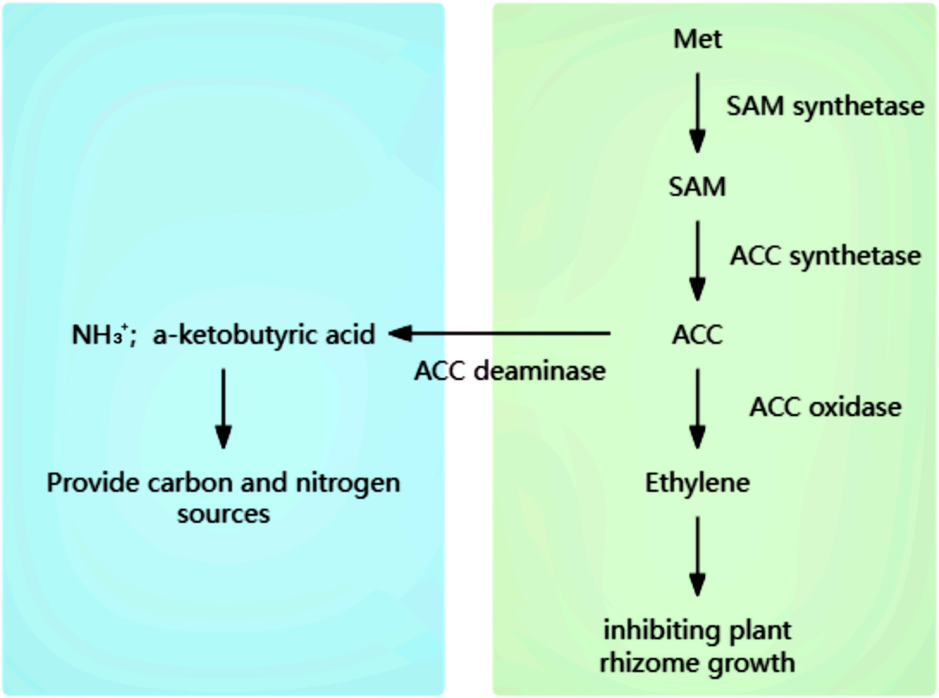

Figure 1. Synthetic decomposition of ACC.

As an emerging green fertilizer, microbial fertilizer stimulates plant growth through a series of life activities by different types of microorganisms secreting plant hormones and other substances. After the application of bacterial fertilizer, the fruit yield and fruiting rate were improved, which played an important role in the sustainable development of agriculture.

2.2.3. Improves Antioxidant Enzyme Activity

Superoxide dismutase (SOD), catalase (CAT), and reduced glutathione oxidase (GSH) were used as antioxidant enzymes to reduce the effects of oxidative stress on plants. SOD significantly reduces the risk of oxidative damage by catalyzing the breakdown of O_2, catalase splits H_2O_2 molecules into water and oxygen, peroxidase is produced in the Golgi apparatus and endoplasmic reticulum, the enzyme is able to break down H_2O_2 and is also involved in cell wall cross-linking, cell wall loosening, lignification, saucer and auxin catabolism, and redox homeostasis, SOD and peroxidases such as CAT and POX are enzyme antioxidant components, and the enzyme and non-enzymatic components of the antioxidant system provide a complex and diverse protective mechanism to maintain ROS homeostasis to avoid oxidation-induced plant cell damage and promote plant growth [19]. Sagar et al. [20] found that the application of *Enterobacter* sp. PR14 in the presence of salt stress enzyme increased the activity of antioxidant enzymes in plants. Zhou et al. [21] found that *W. anomalus* increased the activity of resistance-related enzymes such as PPO, POD, and GU in peach fruit, and enhanced the disease resistance and antioxidant capacity of peach fruit.

Microbial fertilizer can enhance the activity of antioxidant enzymes in plants, improve the ability to scavenge reactive oxygen species, and regulate plant growth.

2.2.4. Stimulates Plant Enzymes and Signaling Pathways in Plants

Secondary metabolites, crucial biochemicals produced by plants through distinct metabolic pathways, play an integral role in plant physiology [22]. These compounds aid in pest and disease resistance, pollination, dispersal, and adaptation to diverse environmental stressors. Beneficial microorganisms can initiate signaling pathways within plants, enhancing the activity of enzymes involved in secondary metabolism and elevating gene expression levels, thereby bolstering plant defense mechanisms and overall health. Actinomycetes, particularly known for their role in antibiotic production, account for approximately 75% of naturally derived antibiotics, with *Streptomyces* being a predominant genus in this context. Researchers discovered a *Streptomyces* griseus strain (A316) in the rhizosphere soil of Chinese cabbage, which was found to inhibit the germination of dormant spores of rhizome pathogens, offering protection against rhizome diseases. Vukelić et al. [23] demonstrated that treatment with *Trichoderma* sp. led to a reduction in the Bioaccumulation Index (BI) of lead (Pb) in two tomato cultivars. They found that the more responsive the cultivar to the treatment, the higher the expression of the swollen hormin gene in the roots, which correlated with better root colonization effects. Arora et al. [24] observed that the combined application of *Piriformospora indica* and *Azotobacter chroococcum* upregulated the transcriptional expression of artemisinin-related genes such as ADS, CYP, DBR2, and ALDH1, indicating a potential for increased artemisinin production. Similarly, Prasanna et al. [25] suggested that the enhancement in acid phosphatase (ACP) activity could be attributed to the active substances present in microbial fertilizers. These substances influence soil ACP activity, facilitating the uptake and utilization of phosphorus nutrients by crops and improving the availability of soil phosphorus.

Further studies indicate that microbial fertilizers significantly boost plant yield, fruiting rates, and root development. Research by Yang et al. [26] demonstrated that a composite microbial fertilizer containing functional microorganisms like *Azospirillum brasilense*, *Bacillus subtilis*, *Licheniformis bacillus*, and *Mucilaginibacter polysaccharea* significantly increased wheat plant height, spikelet number, and yield. Assainar et al. [27] found that microbial inoculants significantly increased grain yield without increasing wheat stem growth, indicating that beneficial microorganisms at appropriate concentrations could promote plant growth and increase grain production.

2.2.5. Nitrogen Fixation, Potassium Solubilization, Phosphorus Solubilization

Nitrogen (N) is an essential element for plant life activities, but atmospheric N_2 cannot be directly utilized by crops. Biological nitrogen fixation transforms atmospheric nitrogen into a form of ammonia that plants can absorb [28]. Nitrogen-fixing microorganisms produce nitrogenase, which converts atmospheric N_2 into ammonia for plant use [8]. Soil nitrogen-fixing bacteria, utilizing nutrients from microbial fertilizers, include symbiotic bacteria like Rhizobia and Frankia, as well as free-living bacteria like Azotobacter and non-symbiotic nitrogen-fixing bacteria, all capable of converting environmental N_2 into ammonia. "Biological nitrogen fixation," mediated by microorganisms through highly sensitive bacterial enzymes, converts atmospheric N_2 into ammonia (NH_3) [29]. For instance, *Rhizobia*, as shown in Figure 2, induce the synthesis of nodulation factors in response to flavonoids secreted by the host, leading to root hair swelling and curling, forming infection chambers, and then penetrating plant root cortical cells through infection threads. *Rhizobia* proliferate within infection threads and differentiate into bacteroids with nitrogen reduction capability in nodules [30].

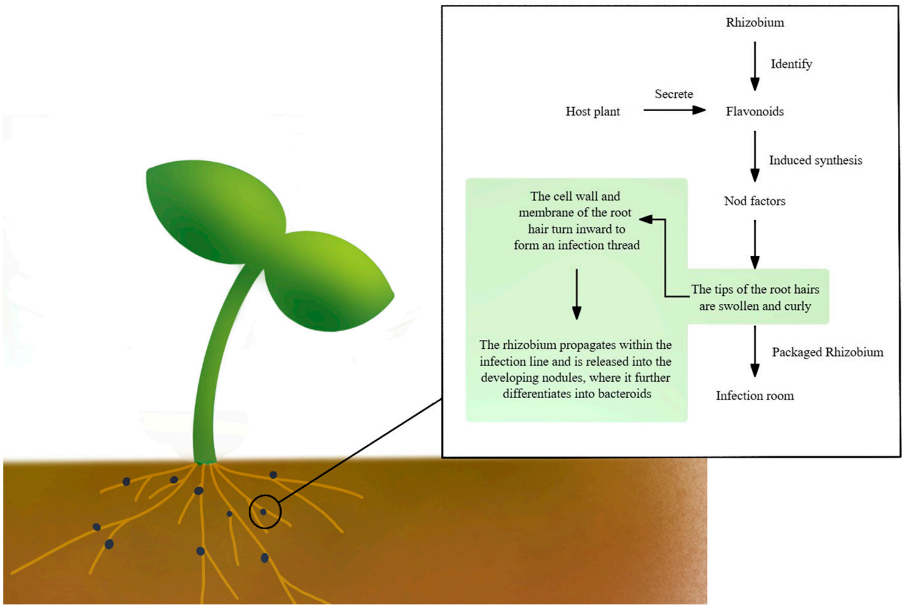

Figure 2. The nitrogen fixation process by Rhizobia.

Potassium (K) regulates plant enzyme reactions, salt tolerance, photosynthesis, and other functions. A lack of potassium in the soil can disrupt plant functions, inhibit growth, and reduce fruit quality [31]. Potassium bacteria, through dissolution and mineralization, convert insoluble potassium in the soil into soluble forms, enhancing plant absorption of potassium, reducing the need for potassium fertilizers, improving utilization rates, maintaining nutritional balance, and enhancing crop quality and yield [32,33]. Potassium bacteria release K from feldspar and aluminosilicate minerals through acidolysis, chelation, exchange reactions, and complexation [34], as well as decomposing organic matter and crop residues [35]. Principal potassium-solubilizing bacteria, such as *Bacillus circulans*, *Bacillus mucilaginosus*, and *Bacillus edaphicus*, break down silicate mineral structures with organic and inorganic acids produced during microbial metabolic activity, releasing potassium into the soil. A study by Chen et al. [35] identified a strain of *Bacillus mucilaginosus* that produced metabolites containing plant hormones and organic acids, promoting potassium absorption in apple seedlings through hormonal stimulation and acidification, thus enhancing growth. Ahmed et al. [7] found that after applying *Bacillus cereus*, soil-available potassium increased by 42%, and the potassium absorption by potato tubers increased by 62%.

Phosphorus (P) is a nutrient essential for the metabolism and development of organisms. Most phosphorus in the soil exists in inorganic forms, with a small amount in organic forms. Soluble inorganic phosphorus can be immobilized, becoming unavailable to plants [36]. Many microorganisms can dissolve insoluble inorganic phosphate compounds, such as *Bacillus*, *Escherichia*, and *Pseudomonas*, by producing organic and inorganic acids, lowering soil pH [37]. The application of microbial fertilizers, through the action of microorganisms within the fertilizer and those enriched in the soil, decomposes organic and inorganic phosphorus in the soil, making phosphorus available to plants. Phosphate-solubilizing bacteria play an important role by solubilizing and mineralizing phosphorus for plant uptake. As illustrated in Figure 3, phosphorus-solubilizing mechanisms mainly include four pathways: secretion of organic acids, secretion of protons, secretion of phosphatases, and other mechanisms, converting insoluble phosphates into free phosphate ions available for plant uptake, including organic acids such as gluconic acid, 2-ketogluconic acid, oxalic acid, citric acid, acetic acid, malic acid, lactic acid, formic acid, succinic acid, propionic acid, and tartaric acid [38]. Microorganisms produce HCO_3^- and NH^{4+} through respiratory action, releasing H^+ and lowering pH to effect phosphorus solubilization. In addition to these pathways, microorganisms absorb and store bioavailable phosphorus during their life activities, releasing it into the soil upon death to increase soil-available phosphorus content. Some phosphorus-solubilizing bacteria also secrete chelating organic substances that release phosphate ions by binding with metal ions.

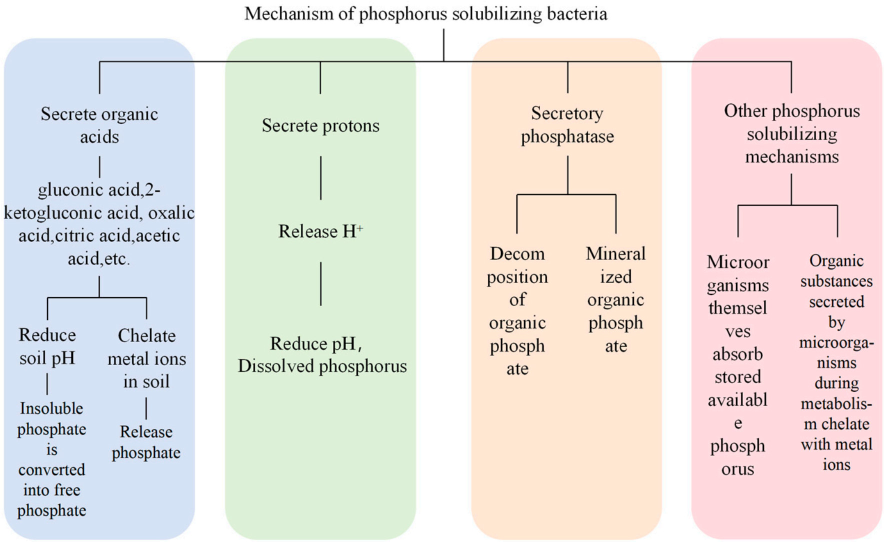

Figure 3. The main phosphorus solubilization mechanisms of phosphate-solubilizing bacteria.

Habibi et al. [39] isolated multiple phosphorus-solubilizing strains from rice plants, including *Paenibacillus*, *Pseudomonas*, and *Enterobacter*, some of which demonstrated the ability to dissolve phosphate minerals (tricalcium phosphate). Prasanna et al. [25] suggested that microbial fertilizers might affect soil acid phosphatase (ACP) activity, enhancing crop phosphorus nutrient absorption and utilization, and improving soil-available phosphorus. Hameeda et al. [40] found that the experiment's mucilaginous *Streptococcus* and *Pseudomonas* sp. could dissolve phosphorus, and photosynthetic bacteria produced metabolites such as plant hormones, antibiotics, and siderophores, promoting maize growth with phosphorus-solubilizing bacteria isolated from compost.

By applying microbial fertilizers containing and enriching soil with nitrogen-fixing, phosphorus-solubilizing, and potassium-solubilizing microorganisms, along with various secondary metabolites and compounds secreted by progressively developing root systems, plants are provided with abundant N, P, K elements, promoting plant growth.

3. The Impact of Microbial Fertilizers on the Structure of Soil Microbial Communities

Soil microorganisms are an indispensable component of the soil ecosystem, playing a crucial role in maintaining soil health and ecological balance. When the structure of the soil microbial community is disturbed, the number of beneficial microorganisms decreases, leading to impaired soil ecosystem functions, proliferation of pathogens, and consequently, adverse effects on plant growth. Beneficial soil microorganisms produce microbial-associated molecular patterns (MAMPs) that plants recognize to differentiate pathogens from non-pathogens and mount appropriate resistance or supportive responses [41].

The diversity and abundance of soil microorganisms serve as important indicators of soil fertility. Increasing the number of beneficial microorganisms in the soil can effectively promote plant growth and development. The application of microbial fertilizers not only fosters the formation of new microbial communities around plant roots but also improves the soil's ecological environment [42]. Studies have shown that the application of microbial fertilizers significantly increases the diversity of soil microbial communities and promotes the proliferation of beneficial bacteria, thereby enhancing microbial activity [43,44]. The probiotics contained in microbial fertilizers activate the soil's native microorganisms and, with the organic matter rich in microbial fertilizers, provide more usable nutrients for soil microorganisms, thus increasing the microbial population. Frankenberger and Dick [45] found a close relationship between alkaline phosphatase, urease, and catalase activities and microbial respiration and biomass in various soil samples, indicating that these soil enzyme activities are optimal predictors of microbial population activity and quality.

The application of microbial fertilizers increases the richness of internal soil microorganisms, inducing the production of substances related to defense responses such as antioxidant enzymes, chitinase, phytoalexins, and phenolic compounds, thereby enhancing crop resistance. As illustrated in Figure 4, after the application of microbial fertilizers, the number of beneficial microbial groups in the soil increases. These beneficial microorganisms compete with pathogens for living space and nutrients, resist pathogen invasion, and further improve soil compaction, promote the formation of soil aggregates, and shift the soil environment towards being more conducive to plant growth.

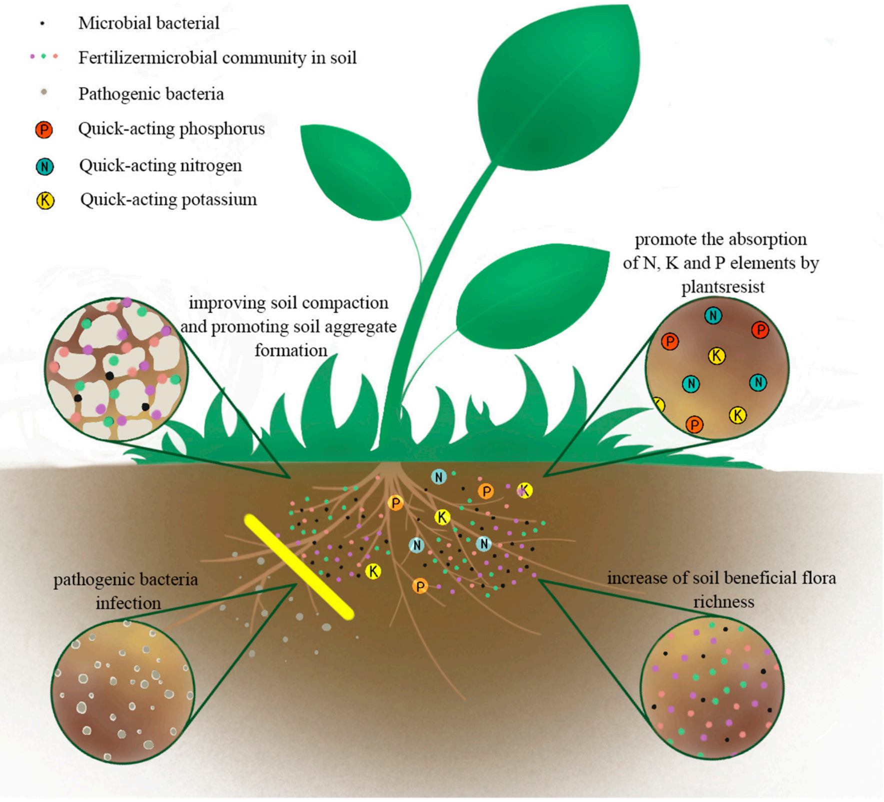

Figure 4. The role of microorganisms in soil.

High-throughput sequencing technology was used to analyze the diversity of bacteria and fungi in soil after the application of microbial fertilizers. Research by Liu et al. [2] showed that the combination of reduced phosphorus fertilizer and microbial fertilizers regulated the populations of pathogenic fungi and beneficial fungi in the soil, forming a microbial community favorable to corn growth. The relative abundance of potential beneficial genera (such as *Streptomyces*, *Bacillus*, *Pseudomonas*, and *Penicillium*) and pathogenic genera increased after the application of microbial fertilizers. Liang et al. [46] found significant changes in metabolic functions on KEGG pathways in treatment groups applying organic microbial fertilizers, affecting soil fungal diversity. In the early stages of *Astragalus membranaceus* growth, the diversity of fungi in the rhizosphere soil was suppressed, but as the plant grew, the secretion of various compounds attracted beneficial microorganisms, increasing the diversity of rhizosphere fungi [41].

Omri et al. [41] found through Illumina MiSeq sequencing technology that the application of organic microbial fertilizers significantly increased the diversity of bacterial communities. Compared to the control group, the microbial community in the treatment group was significantly enriched in various biochemical cycles, including amino acid metabolism, biosynthesis of secondary metabolites, metabolism of coenzymes and vitamins, lipid metabolism, and carbohydrate metabolism [41]. This demonstrates that microbial fertilizers can effectively regulate the structure of soil microbial communities, improving the soil's physicochemical environment and promoting plant growth by increasing soil organic matter content and secreting a variety of secondary metabolites.

High-throughput sequencing analysis of the composition and structure of soil microbial communities after the application of microbial fertilizers provides a deeper understanding of how microbial fertilizers regulate soil microbial communities, increase beneficial microorganisms, and thereby enhance soil biodiversity and fertility. This offers sustainable solutions for agricultural production.

4. The Impact of Microbial Fertilizers on the Structure of Soil Microbial Communities

4.1. Ameliorating Soil Compaction and Promoting Aggregate Formation

The excessive application of chemical fertilizers not only leads to soil salinization and acidification, disrupting the natural soil structure, but also causes soil compaction. This compaction reduces soil porosity, affecting aeration and water permeability, potentially leading to localized soil anoxia [47]. Increased soil hardness poses a serious challenge to plant root growth, impacting the roots' ability to absorb water and nutrients. The application of microbial fertilizers enhances soil microbial diversity and richness, utilizing microbial metabolic activities to improve soil aeration, reduce soil bulk density, and increase the content of soil aggregates, thus effectively mitigating soil compaction. Notably, halophilic microorganisms in microbial fertilizers, through their potassium ion absorption and sodium ion release mechanisms, effectively absorb potassium ions in the soil, addressing soil compaction issues caused by salinization, destruction of soil granular structure, and lack of soil organic matter.

Soil aggregates, as the basic unit of soil structure, play a crucial role in maintaining soil functionality [48]. The size of soil particles, including large particles and small particles (including microaggregates) formed through agglomeration, significantly impacts soil structure and looseness. These aggregates are primary sites for microbial activity, providing habitats for soil microorganisms. The high heterogeneity of soil affects the distribution and activity of microorganisms and enzymes [49,50], directly influencing the cycling and transformation of key nutrients such as carbon and nitrogen, thereby affecting the soil's ecological service functions in agricultural planting. Enhancing the stability of soil aggregates can effectively reduce soil erosion and compaction [51,52]. Microorganisms, especially fungi, arbuscular *Mycorrhizal fungi*, and actinomycetes, play a key role in forming stable soil aggregates by binding soil particles with their extracellular polysaccharides [53,54]. Additionally, the decomposition of fresh organic matter under microbial action produces extracellular polysaccharides and lipids, which also contribute to the formation and stability of soil aggregate structure [55].

The application of microbial fertilizers increases soil microbial diversity, particularly certain fungi that effectively form or stabilize soil aggregates through hyphal entanglement. These microorganisms not only improve soil compaction conditions, increasing soil porosity and aeration, but also enhance soil water permeability, creating favorable conditions for plant root extension and the absorption of water and nutrients.

4.2. Impact of Soil Microorganisms on Soil pH and Organic Carbon

Healthy plant growth requires an appropriate soil pH environment. However, the long-term application of chemical fertilizers can lead to an imbalance in soil pH, adversely affecting crop yield and quality [56]. A low soil pH directly limits plant root development [57], with high concentrations of hydrogen ions in the soil penetrating plant cells, reducing plasma membrane potential, causing cytoplasmic acidification, and damaging internal cell structures. At the same time, high concentrations of hydrogen ions can also damage the cell membranes of soil microorganisms, reducing enzyme production [58,59]. Microorganisms capable of dissolving phosphates, including those that dissolve inorganic and organic phosphates, reduce soil pH by producing low-molecular-weight organic acids, increasing the availability of phosphorus in the soil; these microorganisms solubilize phosphorus in media containing lecithin by acting on lecithin and producing choline enzymes, thereby adjusting soil pH. For example, fungal arbuscular *Mycorrhizal fungi* can promote the secretion of organic acids such as malic acid and citric acid by their host plants, improving soil pH through chelation [60]. *Arbuscular mycorrhizal fungi* can also promote the secretion of organic acids such as valeric acid in alkaline soils, accelerating the degradation of polycyclic aromatic hydrocarbons in the soil, thereby reducing soil pH.

Soil organic matter (SOM) is an essential component of soil organic carbon (SOC), crucial for soil fertility and ecosystem cycling, providing nutrients for plants and promoting plant growth. Due to long-term cultivation, the organic matter content in cultivated soil is relatively low [61]. Research by Ahmed et al. [62] showed that after adding *Bacillus cereus*, the soil organic matter content increased by 10% compared to untreated soil. Maintaining soil organic carbon content is vital for agricultural planting, as a decrease in organic carbon content can lead to reduced crop yield. Biological factors (including microorganisms, plants, animals) and abiotic factors (such as soil physicochemical properties, climate change, human activities) collectively influence the content of soil organic carbon. The chemical composition remaining in plant residues and the decomposition differences of microorganisms affect the formation of soil organic carbon from plant and microbial carbon sources. The application of microbial fertilizers can change the composition of soil microorganisms, increase microbial richness, and the accumulation of substances and residues produced during microbial metabolic processes helps increase soil organic carbon content. At the same time, the increase in the number of microorganisms increases the products and debris in their metabolic processes, thereby changing the organic carbon content in the soil.

By applying microbial fertilizers, the secretion of organic acids by microorganisms in the fertilizer and those enriched in the soil can regulate soil pH, mitigating the inhibitory effect of saline-alkaline soils on plants, and promoting plant growth. Simultaneously, increasing the number of rhizosphere microorganisms enhances microbial carbon sources, forming soil organic carbon for plant absorption and utilization.

4.3. The Impact of Applying Microbial Fertilizers on Soil Pathogens

Plant diseases can be caused by various microorganisms, including bacteria, fungi, nematodes, protozoa, and viruses, with severe infections potentially leading to plant death. Common plant pathogens and Inhibition of pathogenic microorganisms are shown in Table 2. For instance, Trichoderma, as an antagonistic plant pathogenic fungus, plays a key role in controlling tomato Fusarium wilt caused by *Fusarium oxysporum* [63]. *Pseudomonas aureofaciens*, *Trichoderma*, and *Streptomyces* are common microbial agents for disease and pest control [64], which is used to prepare microbial fertilizer to prevent and control pathogenic bacteria and enrich the number of soil microorganisms. As illustrated in Figure 5, biological control utilizes the increased richness of beneficial microbial communities in the soil after applying microbial fertilizers. These beneficial microorganisms, through their proliferation, form dominant microbial communities in the soil, occupying the living space of pathogens and competing with them for nutrients and resources in the soil, thereby inhibiting the growth of pathogens. Antagonistic microorganisms inhibit pathogen growth by secreting toxins or antibiotic compounds, with antibiotics as secondary metabolites that can suppress pathogen metabolism and growth [65]. Research by Chen et al. [35] showed that the *Bacillus amyloliquefaciens* DH-4 strain exhibited antagonistic activity by producing heat-resistant compounds such as surfactins, fengycins, and iturins, which disrupt the ultrastructure of pathogenic cells. Brescia et al. [66] found that *Pseudomonas fluorescens* AZ78 releases diketopiperazines, cyclic lipopeptides, macrolides, and macrolactone antimicrobial secondary metabolites to combat plant pathogens and Gram-positive bacteria.

Table 2. Common plant pathogens.

Common Plant Pathogens	Main Pathogenic Bacteria	Inhibition of Pathogenic Microorganisms	Reference
Rice blast	*Magnaporthe oryzae*	*Fusarium* sp., *Armillaria novae-zelandiae*, *Falciphora oryzae*	[67]
Gray mold	*Botrytis cinerea*	*Bacillus subtilis*, *Bacillus amyloliquefaciens*	[67]
Southern corn rust	*Puccinia* spp.	*Doru luteipes*	[68]
Wheat scab, corn ear rot, Corn stalk rot, etc	*Fusarium graminearum*	*Bacillus cereus*, *Azotobacter nigricans*	[69]
Cotton wilt	*Fusarium oxysporum*	*Bacillus amyloliquefaciens*	[70]
Sorghum anthracnose	*Colletotrichum sublineolum*	*Coccidium*, *Trichoderma harzianum*, *Fusarium oxysporum*	[71]

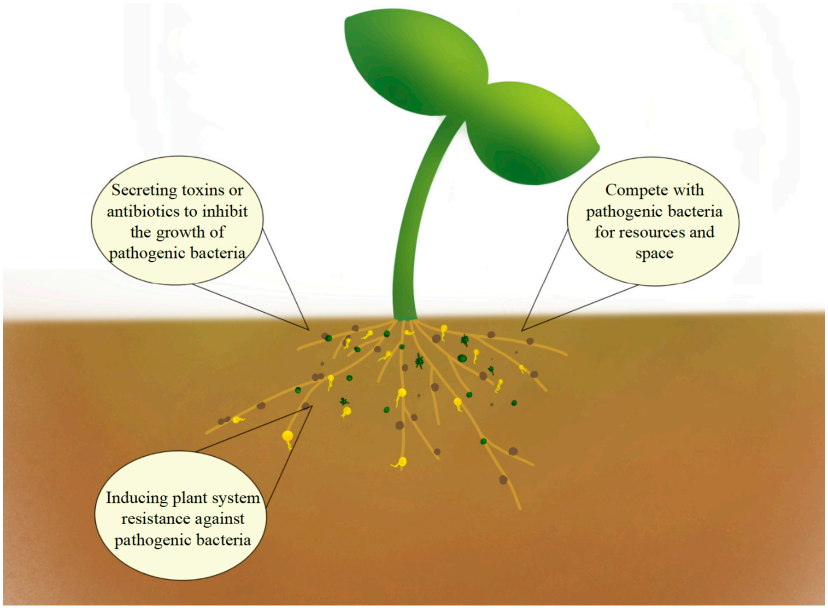

Figure 5. Microorganisms assisting plants in pathogen resistance.

In modern agricultural production, the excessive use of chemical fertilizers and pesticides has led to ecological degradation, decreased farm productivity, and damage to soil aggregate structure, causing issues like soil compaction and severely disrupting the agricultural environment [72]. Microbial fertilizers, through the metabolic activities of microorganisms, can degrade pesticide residues in the soil, purify the soil, and enhance its aeration, thus promoting root growth. For instance, ethyl parathion, a common organophosphorus compound used in pest control [73], has been shown by Singh et al. [74] to be degraded by *Pseudomonas pseudoalcaligenes* PS-5 into O-methyl-N-acetylphosphoramidate. Moreover, microorganisms can improve soil physicochemical properties, increase microbial diversity, and regulate soil enzyme activity, positively affecting the rhizosphere microecology and significantly impacting plant growth and development [75].

With its natural, non-toxic, harmless, and non-polluting characteristics, microbial fertilizer restores the soil environment, reduces the harm of pests and diseases, and maintains the green environment through its own life activities.

5. Conclusions

This study demonstrates that microbial fertilizers significantly enhance the richness and diversity of soil microorganisms, crucial for maintaining the soil microecological balance and improving the soil environment. Through the secretion of various secondary metabolites, proteins, enzymes, and plant hormones, microbial fertilizers stimulate plant growth and enhance the absorption and utilization of essential nutrients such as nitrogen (N), phosphorus (P), and potassium (K). The application of microbial fertilizers has proven effective in the cultivation of a wide range of crops, offering a sustainable alternative to chemical fertilizers by reducing agricultural input costs, mitigating environmental impact, and promoting eco-friendly farming practices.

Globally, regulatory frameworks such as Brazil's Law 6894/80 ("Fertilizer Act"), the United States' state-level regulations, and China's "General criteria for quality and safety evaluation of microbial fertilizer" play pivotal roles in ensuring the quality, safety, and efficacy of microbial fertilizers. These regulations set standards for microbial fertilizer production, ensuring their beneficial impact on agriculture while protecting environmental health.

Looking forward, the development and application of microbial fertilizers are expected to shift towards employing genetically modified strains with high functional pleiotropy and production efficiency. Such advancements will further reduce the reliance on chemical fertilizers, bolster plant growth, improve crop yields, and safeguard soil health, thereby contributing significantly to the sustainable development of agriculture. However, challenges such as elucidating the mechanisms of interaction among compound microbial strains and potential changes during the production process highlight the need for ongoing research. Future studies should focus on understanding the action mechanisms of microbial fertilizers, screening for superior microbial strains, developing multifunctional microbial fertilizers, and optimizing their scientific application to maximize benefits for sustainable agriculture.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy14030609/s1, Figure S1: (A) Key words time change chart of microbial fertilizer related research; (B) National contribution map of microbial fertilizer related research; Figure S2: Publication Volume and Trends in English Liter-ature from 2000 to 2025; Figure S3: Citation Relationship between the Knowledge Frontier and the Knowledge Base Literature on Microbial Fertilizers.

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