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Soil Microorganisms in Agricultural Fields and Agronomic Regulation Pathways

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Abstract: Agricultural soil microorganisms play a crucial role in farmland ecosystems and are integral to the material cycle in these environments. The composition and abundance of soil microorganisms are influenced by agronomic measures that alter the soil microenvironment. These changes are pivotal to enhancing crop resistance, maximizing yield, and facilitating nutrient cycling in farmlands. Drawing on prior research advancements, this study systematically examined the functions of soil microorganisms, the effects of various agronomic measures on their populations, and the ways in which agronomic measures regulate soil microorganisms, and this article offers a comprehensive study of agricultural influences on microorganisms. Additionally, it outlines key areas for future research on soil microorganisms in farmlands, aiming to provide valuable insights for the sustainable development of farmland ecosystems.

Keywords: farmland ecosystem; soil microorganisms; microbial function; agronomic measures

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1. Introduction

Microorganisms encompassing a vast array of forms across bacterial, archaeal, and eukaryotic domains pervade all ecosystems on Earth with unparalleled diversity and abundance [1,2]. Their multifaceted roles have paramount relevance for our efforts to cycle geochemical elements, explore global climate change, elucidate natural life mechanisms, sustain ecological services, curb greenhouse gas emissions, and enhance soil health and crop productivity [3–5]. Particularly in agricultural fields, soil microorganisms play a pivotal role in fostering ecosystem equilibrium, facilitating nutrient cycling, and bolstering crop development.

Globally, climate change significantly affects soil microbes, altering the soil nutrient composition and structure [2,6,7]. In agricultural settings, agronomic measures such as soil tillage, crop diversification, fertilizer transport, and water management enhance agrarian productivity while modifying the farmland microenvironment, thereby influencing soil microbes [8–10]. For example, soil tillage mechanically destroys and reconstructs the original soil, leading to changes in soil aggregates, bulk density, porosity, organic matter content, and other environmental factors that affect soil microorganisms [11–13]. Crop diversification alters soil microbial populations through variation in root secretions [3,9,14]. Fertilizer usage modifies the soil nutrient environment and affects the soil microbes [15,16]. Likewise, water management affects soil microbes by regulating soil effectiveness [6,7,17]. Farmland ecosystems, distinguished by human intervention, exhibit distinct microclimates shaped by crops and artificial soil interventions that profoundly influence the composition and function of soil microorganisms [18,19]. Hence, optimizing farmland management practices to improve the soil microbial structure and functional diversity is crucial. Addressing this scientific challenge is crucial for maximizing crop production in modern agricultural systems.

As agricultural science and technology advances, enhancing crop yields and promoting carbon sequestration in farmland soil through soil microorganisms has emerged as a focal point in sustainable agriculture research. Therefore, this study reviewed the functions of soil microorganisms in farmland, examined the regulatory role of agronomic measures on these microorganisms, and analyzed the pathways through which agronomic practices affect soil microbes, and, in doing so, we anticipated future research directions. Our aim in conducting this study was to offer insights for optimizing farmland management strategies and harnessing the full potential of soil microorganisms to promote sustainable agricultural development by reviewing the research of other authors.

2. Functions of Agricultural Soil Microorganisms

2.1. Crop Growth

Soil microorganisms interacting with crops play a pivotal role in promoting crop growth, increasing yield, and enhancing resilience to abiotic stress (Figure 1). Research has indicated that soil nitrogen-fixing bacteria can enhance crop growth by immobilizing atmospheric nitrogen and engaging in mutual recognition and molecular communication with legume crops [14,20]. Conversely, crops actively recruit and shape inter-root microbial communities through root secretions including sugars, phenolics, amino acids, and ketones, which serve as nutrients for beneficial microorganisms, thereby fostering optimal conditions for crop growth [10,21]. Microorganisms such as *Pseudomonas* spp., nitrogen-fixing *Spirochetes* spp., and *Bacillus* spp. modulate the levels of various hormones such as growth hormone, gibberellin, and abscisic acid via the crop hormone regulatory network, thus influencing crop growth and development [22,23].

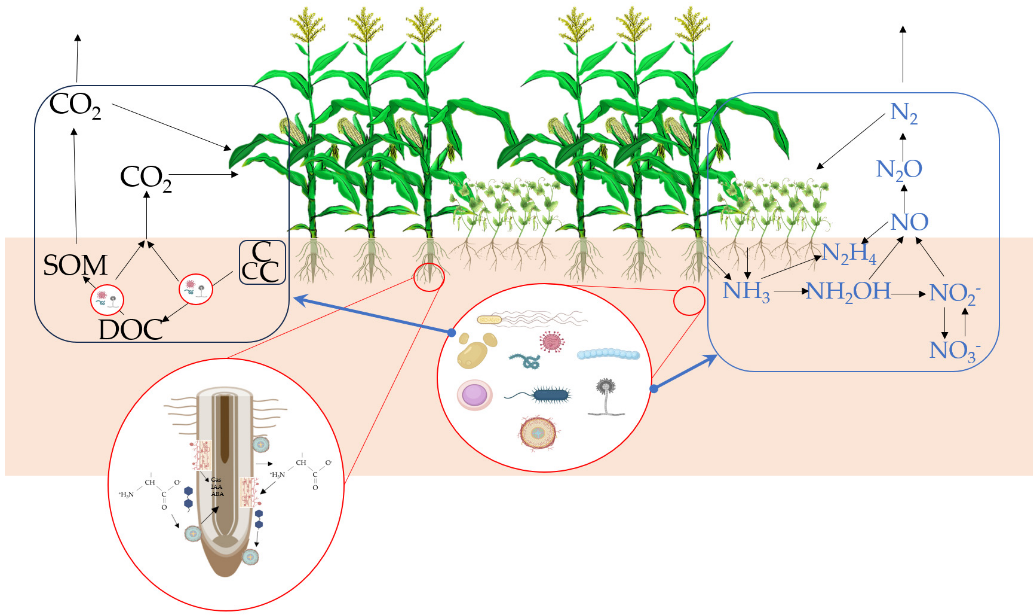

Figure 1. Functions of beneficial and pathogenic soil microorganisms in agroecosystems.

2.2. Nutrient Cycling in Agricultural Land

Soil microorganisms play a crucial role in nutrient cycling within agricultural ecosystems, affecting this cycle through organic matter decomposition, nutrient release, facilitation of plant uptake, and interactions with other organisms (Figure 1). Research indicates that the α-diversity and β-diversity of bacteria in agricultural soils significantly correlate with the soil multinitrogen cycling index, with saprophytic and tufted arbuscular mycorrhizal fungi notably accelerating the decomposition of apoplastic materials [24,25]. Studies have demonstrated that microbial carbon utilization efficiency (MCE), a comprehensive indicator of microbial impact on soil organic carbon, correlates with increased biosynthesis of microbial carbon metabolism. Higher MCE levels facilitate organic matter formation in the soil and improve the soil carbon sequestration capacity [8,26]. Moreover, microorganisms contribute to nitrogen cycling in farmland ecosystems through processes such as assimilation, ammonification, nitrification, and denitrification. For example, nitrogen-fixing microorganisms facilitate ammonium uptake by leguminous crops through symbiosis, while diffused ammonium enriches the surrounding soil, benefiting other microorganisms. Simultaneously, nitrifying microorganisms (such as *Skermanella* and *Azospirillum*) convert ammonium into gaseous nitrogen compounds, which are released into the atmosphere [14,27]. Phosphorus, a limiting nutrient in agricultural soils, exhibits low mobility. Soil microorganisms, such as *Bacillus* spp. and *Pseudomonas* spp., facilitate phosphorus uptake by crops through processes including uptake, solubilization, and translocation [28].

2.3. Stress Resistance

In harsh environments, such as high temperatures and drought, crop growth is often impeded or even halted, but beneficial microorganisms that interact with crops can improve their resilience to such adverse conditions, e.g., enrichment of Gram-positive bacteria and depletion of Gram-negative bacteria [29] (Figure 1). Research has revealed that drought increases the abundance of actinomycetes in the soil, particularly thick-walled mycorrhizal fungi [30,31], which significantly contribute to crop tolerance under drought stress. These microorganisms aid crop tolerance to drought by secreting plant growth regulators, producing extracellular polysaccharides, synthesizing ACC deaminase, and enhancing antioxidant enzymes in crops. Additionally, mycorrhizal fungi assist crops in accessing water beyond the inter-root zone through their mycelial network, thereby enhancing crop stress resilience [22].

Most soil microorganisms collaborate with crops to protect them against pathogens and pests, although some may facilitate pathogen invasion (Figure 1). Research has indicated that the proliferation of beneficial soil microorganisms competes with pathogens for resources, thereby limiting the space available to pathogens [32]. Furthermore, beneficial microorganisms can prey on certain pests. For example, fungi such as *Streptomyces* spp. and *Paenibacillus* spp. can target pests such as the European gold beetle and aphids, while others can infect and kill nematodes by invading nematode eggs and sporocarps through fungal mycelial networks [22,32,33]. Moreover, some beneficial microorganisms induce crops to produce defensive compounds such as antibiotics and lytic enzymes. For example, soil feedback initiated by microbial activity can trigger the production of secondary metabolites, such as benzoxazines, by plants, activating the salicylic acid signaling pathway and subsequently enhancing defense mechanisms against pathogens [4]. However, the intricate relationships among microorganisms, including intra- and interspecies interactions as well as transboundary interactions, may sometimes lead to microorganisms aiding pathogens in invading crops by forming partnerships with them [34].

2.4. Climate Regulation

Soil microorganisms play a crucial role in soil greenhouse gas emissions, which may lead to climate change dynamics. Soil greenhouse gas emissions and carbon sequestration are closely intertwined with their metabolic activities. They metabolize carbon dioxide in the soil, releasing it into the atmosphere through respiration [22]. These microorganisms regulate the atmosphere–soil carbon cycle by participating in soil carbon turnover. For example, soil microbial decomposition of apomictic litter and heterotrophic respiration release CO_2 into the atmosphere, contributing to nearly half of the global terrestrial carbon emissions (Figure 1). This process exacerbates the greenhouse effect [35,36]. Furthermore, some soil microorganisms generate nitrous oxide through nitrite-oxidizing bacteria's involvement in nitrification and denitrification, though a distinct group, including ammonia-oxidizing bacteria and archaea, converts nitrate to ammonia via reduction reactions. Agricultural soils, constituting a critical source of nitrous oxide emissions, contribute over 65% of global emissions [5,27,37]. Meanwhile, methane is a significant greenhouse gas, and microorganisms contribute to two-thirds of the global methane emissions. Methanogenic bacteria, predominant in anaerobic environments such as agricultural systems (e.g., rice paddies, swamps, and floodplains), play a central role in methane production [22]. Concurrently, methane-oxidizing bacteria help mitigate atmospheric methane levels. Research indicates variations in methane-oxidizing bacterial populations between rice paddies and dryland soils, with methanogens being prevalent in rice paddies and drylands. In particular, dryland soils act as methane sinks owing to the limited or absent methane production [22,38].

2.5. Pollutant Degradation

Agricultural soil pollution poses a significant challenge to sustainable agriculture, with approximately 64% of the global agricultural land contaminated by pesticides, as well as other pollutants, such as chemical fertilizers, plastics, and heavy metals [22,39]. Microorganisms, serving as primary decomposers and consumers, play a crucial role in pollutant degradation and soil remediation. Research indicates that naturally occurring pollutants undergo microbial metabolism within the ecosystem cycle, whereas xenobiotics are transformed by the broad-substrate properties of soil microorganisms and enzymes [40,41]. However, polyethylene plastics, commonly used as mulch films, pose a challenge because they are resistant to microbial degradation over prolonged periods in agricultural fields. Furthermore, some microorganisms have negative effects, such as when siderophore-producing bacteria exacerbate pollution by immobilizing heavy metals or when *Achromobacter* and *Acinetobacte* convert nitrogen fertilizers into nitrites [25,42,43].

3. Roles of Agronomic Measures in Soil Microbial Regulation

Soil microorganisms are pivotal in farmland ecosystems as they regulate crop growth, facilitate nutrient cycling, and foster crop health. However, regional variations in soil microorganisms are common. Therefore, enhancing soil microorganisms by leveraging local indigenous soil microbial communities through a combination of agronomic measures has emerged as a natural and sustainable strategy.

3.1. Soil Cultivation

Soil tillage plays a crucial role in altering soil microbes, modifying the soil structure, and fostering crop growth (Figure 2). However, conventional tillage practices have been observed to disrupt the original soil microbial community structure, leading to a decrease in soil fungal abundance and the proliferation of eutrophic microorganisms [44,45]. In contrast, natural tillage methods, devoid of chemical fertilizer and pesticides, promote symbiosis between leguminous crops and nitrogen-fixing microorganisms [18,46,47]. This enhances soil microbial diversity, fostering the emergence of probiotic flora that are absent in conventional tillage systems, including *Rhizobium*, *Streptomyces*, and *Burkholderia*. Consequently, natural tillage exhibits greater soil microbial abundance and diversity and a more intricate structural network [18]. Conservation tillage regulates soil functional microbial communities, enhancing both the richness and complexity of microbial networks [48,49]. This practice fosters the enrichment of diverse phyla, such as Actinobacteria, Bacteroidetes, Ascomycetes, and thick-walled bacteria, thereby improving the microbial utilization of amino acids, carbohydrates, and hydroxy acids [48–51]. Notably, reduced tillage enhances total microbial populations, with increased bacterial and fungal abundance, whereas no tillage tends to positively impact fungi, both of which promote oligotrophic soil microbial populations. Additionally, straw return to the fields elevates soil microbial aroma indices and stimulates the expression of functional nitrogen-cycling genes, enriching nitrogen-fixing microbes [8,50]. Meanwhile, conservation tillage further fosters the growth of oligotrophic prokaryotic communities, significantly increasing the α-diversity of surface soil microorganisms and colonization of microbial aggregates such as tufted mycorrhizal fungi and nematophagous fungi [8,22,52].

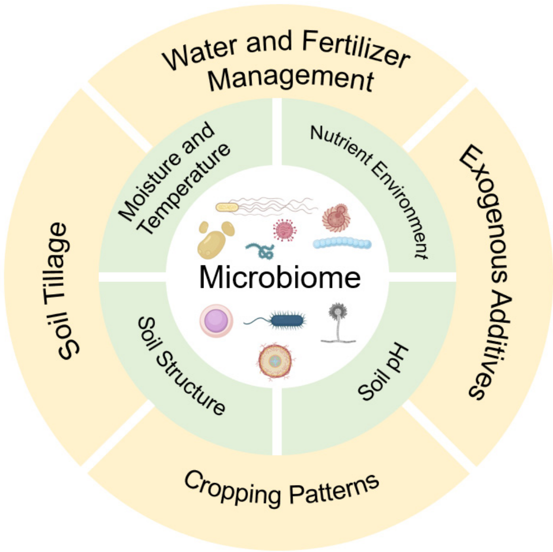

Figure 2. Impact of agronomic measures on soil microbial composition.

3.2. Cropping Systems

Cropping systems play a significant role in shaping soil microorganisms by influencing aboveground crop type and structure (Figure 2). Crops contribute nutrients to soil microorganisms through root secretions and litter, with specific root exudates attracting particular microbial flora to colonize the crop root system and its vicinity. Crop diversification alters the composition of microorganisms in the soil, e.g., increasing the abundance of tufted mycorrhizal fungi and decreasing the abundance of nitrifying spirochetes in grass–bean intercropping systems [52,53]. Continuous monocropping throughout the year tends to decrease microbial diversity and foster the proliferation of pathogenic microorganisms, particularly pathogenic bacteria [53,54]. In contrast, crop diversification, such as intercropping, enhances the Shannon index of soil microorganisms and increases the archaea abundance. For instance, intercropping grass and bean promotes the abundance of nitrogen-fixing and denitrifying microorganisms involved in the soil carbon and nitrogen cycles [53,55,56]. Studies have demonstrated that increasing the number of crop rotation species significantly increases the number of nodes and edges in the soil microbial network, leading to improved fungal diversity. However, this practice does not significantly affect bacterial diversity. Nonetheless, crop rotation fosters a more extensive and stable microbial community in the soil, promoting nutrient cycling by soil microorganisms [57,58].

3.3. Water and Fertilizer Management

Soil moisture plays a crucial role in shaping soil microorganisms, especially aerobic and anaerobic microorganisms including *Methylomonas* and *Methanobacterium formicium* in agricultural fields [35], primarily sourced from atmospheric precipitation and artificial irrigation, affecting microorganisms at both spatial and temporal scales (Figure 2). Persistent precipitation has been found to significantly reduce fungal diversity and consistency, resulting in increased unpredictability of the soil microbial community composition [59]. Likewise, different irrigation methods and water types exert varied effects on soil microbes. Water-saving irrigation methods enhance soil microbial diversity when compared with conventional methods, with an increased abundance and complexity of soil-denitrifying bacteria [60]. In research using different irrigation water types, it was found that farm wastewater tended to cause a decrease in soil microbial function compared to natural water bodies such as lake water, while treated industrial and domestic wastewater significantly increased the abundance of bacteria and suppressed the abundance of fungi in the soil [61,62]. Additionally, anaerobic conditions resulting from irrigation (indeed, other agronomic practices such as changes to ground cover can also lead to anaerobic conditions) stimulate rapid proliferation of anaerobic microbial communities. Moreover, studies investigating various irrigation water types, including freshwater, brackish water, and reclaimed water, have revealed significant differences in microbial communities. Short-term irrigation with different water types increases soil microbial diversity, although the long-term effects remain uncertain [63].

Soil fertilization is essential for maintaining soil fertility and promoting crop growth (Figure 2). Inorganic fertilizers, while providing direct nutrients for crop growth, can lead to a C/N imbalance and loss of carbon for microbes in the soil, limiting carbon sources for microorganisms [64]. This imbalance fosters a microbial structure in which oligotrophic microorganisms dominate the soil community, resulting in a notable reduction in the soil bacterial diversity. Additionally, there is an upsurge in the microbial decomposition of organic matter within aggregates as a response to evading carbon source limitation [15,16]. Conversely, organic fertilizers enhance soil microbial abundance and diversity, fostering integration with existing microbial communities and altering soil function [16,64,65]. However, fresh organic fertilizers notably increase soil fungal diversity and the abundance of soil-borne-disease-associated microbial communities. Despite their temporary presence, these exogenous soil microbial communities activated by organic fertilizers increase the risk of crop pathogenicity. Therefore, it is necessary to enhance the process of controlling the native pathogenic microorganisms present in organic fertilizers [28].

3.4. Pest and Weed Control

Chemical pesticides are commonly used to manage pests, diseases, and weeds. Early pesticides containing high levels of heavy metals led to soil and crop contamination, altering the composition of soil microorganisms [22]. Although the use of synthetic organic pesticides has mitigated this issue, their impact on soil microorganisms remains significant. Studies reveal that residues from these pesticides increase the diversity and abundance of pesticide-degrading microorganisms but inhibit bacterial communities and some nitrogen-fixing microorganisms including *Rhizobium Frank* [22,38]. Additionally, synthetic organic pesticides have been shown to alter soil organic matter stability, and the genetic diversity of soil microorganisms such as wuyiencin promoted the enrichment of *Streptomyces* spp. microorganisms, but the relative abundance of azoxystrobin and the carbendazim actinomycetes phylum decreased [66,67]. Therefore, biologics are increasingly favored in agricultural production because of their lower chemical residues. Although biologics effectively control pests and diseases while promoting crop growth and soil health, further research is needed on the potential cross-fertilization of exotic microbial populations with indigenous populations [68].

In various agricultural practices, including but not limited to those mentioned above, agronomic measures can directly or indirectly impact soil microorganisms. The implementation of individual measures or their integrated application has diverse effects on soil microbial community structure and abundance. In rice paddies, for example, the anaerobic conditions resulting from irrigation often allow for rapid colonization of methanogenic bacteria and the production of large quantities of methane [69]. Hence, selecting the optimal combination of agronomic measures is crucial to harness the benefits of microorganisms, particularly indigenous microorganisms, and to enhance nutrient uptake by crops. For example, crop diversification changes aboveground biodiversity while also contributing to the stabilization of microbial diversity and communities in the soil [57,58]. This selection plays a pivotal role in maintaining the stability of farmland ecosystems and fostering beneficial soil–microbe–crop interactions. Therefore, choosing the optimal combination of agronomic measures to maximize the functions of beneficial microorganisms, especially indigenous ones, and to enhance crop nutrient uptake holds significant importance for farmland ecosystem stability and favorable soil–microbe–crop dynamics.

4. Pathways of Agronomic Measures to Regulate Soil Microorganisms

Soil microorganisms are affected by their surrounding environment [7,30,70]. Human activities constitute substantial interventions in farmland ecosystems by altering the soil microenvironment through practices such as soil tillage, planting systems, and water and fertilizer management [48,50,58,60]. These agronomic measures directly or indirectly induce adaptive changes in the soil microorganisms in agricultural soils (Figure 2). Therefore, studying human activities may reveal opportunities for enhancing the combination of agronomic measures to optimize the living conditions of soil microorganisms.

4.1. Nutrient Environment and Soil Microorganisms

Agronomic practices, such as soil tillage and water and fertilizer management, significantly modify the nutrient environment in the soil, particularly carbon, nitrogen, and phosphorus sources, water availability, and other materials crucial for microbial utilization (Figure 2). Non-autotrophic microorganisms are notably affected by these changes, with examples including *Sulfolobus acidocaldarius* [22,52,69]. Various nutrient management practices induce distinct alterations in soil nutrient contents and ratios, particularly in the C/N ratio. These alterations lead to the formation of diverse microbial communities. For instance, soils with low organic matter contents tend to harbor high levels of oligotrophic microbial taxa, whereas soils with high organic matter contents inhibit the growth of most oligotrophic microorganisms [17,64].

Ammonia serves as a primary nitrogen nutrient source for nearly all microorganisms, although some can also utilize nitrate nitrogen and organic nitrogen sources, such as amino acids. Moreover, a limited number of microorganisms are capable of nitrogen fixation [71]. Changes in the soil nitrogen content directly influence microbial abundance and diversity, with high and low C/N levels determining whether nitrogen-limited or carbon-limited microorganisms dominate [2,64]. Additionally, microbes, biotin, and various inorganic salts containing phosphorus, sulfur, and potassium serve as significant nutrient sources for microorganisms and are essential for enzyme activity; for instance, crop–microbe interactions in effective phosphorus-rich soils promote crop growth and allow for the enrichment of the *Acidobacteria* phylum in the soil [72].

Water constitutes approximately 70–90% of the microbial cell mass, making it a crucial component of the microbial cell composition. The efficacy of soil water profoundly affects the abundance and diversity of soil microorganisms (Figure 2). Changes in soil water, along with other nutrients, serve as signals of variations in the nutrient environment that are received by receptors on microbial cell membranes. These signals are then transmitted to the genome via the phosphorylation of cytoplasmic proteins [8,22]. Consequently, microbes respond to these signals by altering the structure of the soil microbial community [8,65]. For example, excessive soil moisture creates an anaerobic environment, promoting the rapid multiplication of anaerobic microorganisms and altering the original microbial structure. Conversely, aerobic microorganisms such as methane-oxidizing bacteria dominate under aerobic conditions [3,49].

In addition to the primary nutrients essential for microorganisms that have been mentioned above, growth factors such as metallic elements, pyrimidines, and purines also serve as nutrient sources for certain microorganisms [22]. Different microorganisms have varying requirements for growth factors. For instance, *Streptococcus* spp. and *Streptococcus mingitensis* have a high demand for soil vitamins [2]. Through agronomic measures, people regulate the carbon, nitrogen, phosphorus, sulfur, and water contents of soils to ensure and enhance crop growth. However, these measures also induce alterations in the contents and proportions of multiple microbial nutrients in soils to differing degrees. This, in turn, shapes the structures and abundance of microbial communities unique to specific regions, crops, and agronomic practices.

4.2. Soil Structure and Microorganisms

Various agronomic measures, such as soil tillage, organic fertilizer application, and irrigation, influence the soil structure differently. Research indicates that practices such as no tillage, straw return, and organic fertilizer usage can augment macroaggregate numbers in the soil, whereas irrigation can variably change the tri-comparison in the soil [73,74]. These alterations in the soil structure directly affect the habitat of soil microorganisms and constitute a primary driver of shifts in soil microbial communities (Figure 2). Studies have revealed a strong correlation between soil aggregate size and microbial community composition. Larger aggregates tend to harbor higher bacterial and fungal abundance, with bacteria predominantly found in microaggregates, whereas eutrophic communities dominate microbial communities within aggregates [20,75]. For example, conventional tillage disrupts the original soil structure, exchanging deep soil with surface soil and subjecting it to wet and dry cycles, thereby increasing aggregate mobility [8,19]. As a result, this process alters the habitat of soil microorganisms, destroying the original fungal mycelial network, accelerating organic matter decomposition, and favoring the proliferation of symbiotic bacteria. Conversely, it compresses the habitat of non-symbiotic bacteria, leading to the rapid growth of saprotrophic fungi and crop pathogens, consequently affecting soil microbial diversity [22,51].

In addition, soil microorganisms are influenced by the soil tripartite ratio, with certain functional genes displaying heterogeneity corresponding to differences in this ratio [70]. Soil microbial diversity significantly fluctuates in soils with varying tripartite ratios because of differential oxygen availability sensed by soil microorganisms. For example, aerobic microorganisms thrive in well-aerated soils, whereas anaerobic microorganisms flourish in oxygen-depleted environments, a distinction linked to their respective adaptations. Aerobic microorganisms have evolved enzymes such as peroxidases and superoxide dismutases to detoxify oxygen-containing compounds [1,2], whereas anaerobic microorganisms lack the capability to metabolize oxygenated toxins and quickly perish under aerobic conditions [2,20]. This dichotomy explains the marked difference in methane emissions between arid regions and rice fields.

4.3. Response of Soil Microorganisms to Other Environmental Changes

Soil microorganisms are influenced by the soil temperature, pH, and other factors [7,17,76,77]. Measures such as altering the ground cover can induce varying degrees of changes in soil temperature (Figure 2). Studies have revealed that elevated soil temperature significantly affects the abundance of *Actinobacteria* and Scatteromycetes phyla in soil. Different microbial communities, namely eutrophic and oligotrophic microorganisms, exhibit distinct responses to temperature shifts owing to their diverse life history strategies [31,78]. Moreover, agronomic activities featuring exogenous material inputs may alter soil pH over short- or long-term periods, and the consequent effects on soil microorganisms, although gradual, are significant. Soil pH serves as a crucial factor for modulating the soil nitrogen cycle microorganisms. For instance, soil acidification can notably inhibit the abundance of nitrifying microorganisms [72]. Furthermore, the impact of global change on soil microorganisms is also mediated through alterations in soil pH [26].

In the growth of soil microorganisms, their biological response to changes in the environment exhibits similar patterns. For example, soil microorganisms tend to adjust by activating or deactivating specific genes in response to these changes, or they may enter a dormant state or perish if unable to cope [2]. Over extended evolutionary periods, certain microorganisms have developed extreme adaptations to their environment. In addition to abiotic factors, interactions among organisms play a crucial role in shaping the structure of soil microbial communities, with limited competition significantly contributing to community stability [1,33,77].

5. Future Development Directions

Agricultural soil microorganisms are vital components of farmland ecosystems and play pivotal roles in nutrient cycling, crop health, and soil vitality. Optimizing agronomic measures to regulate soil microorganisms and ensure the health of soil–microorganism–crop systems represents a pivotal advancement in sustainable agriculture. Therefore, deeper research into soil microorganisms in farmlands should focus on the following aspects.

1. Evolution of soil microorganisms: Investigating the development and succession of soil microorganisms can shed light on the formation of microbial community structures. Understanding how soil microorganisms evolve in farmland ecosystems and respond to agronomic measures is essential for optimizing agricultural measures.
2. Interaction between soil microorganisms and crops: Soil, microorganisms, and crops form a cohesive unit, with microorganisms creating a conducive environment for crop growth and nutrient uptake. Exploring the interaction and co-evolution between soil microorganisms and crops reveals the microbial regulatory mechanisms affecting crop health, nutrient uptake, and pest resistance.
3. Resource discovery and utilization of soil microorganisms: Soil harbors vast microbial resources with untapped potential. Identifying and harnessing new beneficial microbial resources and studying their applications in agriculture, energy, and healthcare offers promising avenues for sustainable development.

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