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MORTIERELLA SPECIES AS BENEFICIAL FUNGI FOR ENHANCING PLANT GROWTH IN AGRICULTURAL SOILS

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Abstract

Agriculture, as the cornerstone of global sustenance, faces the dual challenge of increasing crop yields while minimizing environmental harm. The intricate interplay between plants and soil microorganisms, particularly fungi, has garnered significant attention for its potential to boost plant growth, enhance nutrient uptake, and combat soil-borne diseases. Among these soil microorganisms, Mortierella species have emerged as essential contributors to soil health and fertility. These fungi, known for their versatility and capacity to form mutualistic associations with a wide range of crops, hold the promise of transforming modern agriculture. Mortierella species stand as allies to sustainable agriculture, forging a harmonious alliance between crop productivity and ecological well-being. The review underscores the potential for Mortierella-based strategies to address the pressing challenges of food security and environmental sustainability. As agriculture evolves, the integration of Mortierella species promises a path toward a more sustainable and prosperous future.

Keywords: mycorrhizal, mortierella, agriculture, soil, growth, nutrient, sustainability, biodiversity, biocontrol.

1. INTRODUCTION

Agriculture, as the primary source of sustenance for the world's growing population, faces a critical challenge - how to increase crop yields while simultaneously minimizing environmental harm. Soil health and nutrient availability are pivotal factors in achieving this balance. The interplay between plants and soil microorganisms, particularly fungi, has gained considerable recognition due to its potential to boost plant growth, enhance nutrient uptake, and counter soil-borne diseases.

In agriculture, the soil is more than just a medium for plant anchorage; it's a complex ecosystem teeming with life. Among the myriad of soil microorganisms, fungi have emerged as essential contributors to the health and fertility of soils. These microorganisms play a vital role in nutrient cycling, organic matter decomposition, and soil structure development [1].

Fungi, in particular, hold a special place in the soil ecosystem due to their capacity to form mutualistic associations with plants. These symbiotic relationships have far-reaching implications for both the plant and the soil. One group of fungi that has gained prominence in this context is Mortierella species.

Mortierella species belong to the subphylum Mortierellomycotina and are renowned for their ability to form mutualistic associations with various plants. These associations are crucial for the overall health and productivity of agricultural ecosystems. Mortierella spp. exhibit remarkable versatility and have been

identified in diverse soil types and climatic conditions [4,5].

The rationale for this review lies in the need to comprehensively explore the beneficial effects of Mortierella species on plant growth and their potential applications in agriculture. Mortierella spp. have demonstrated the capability to enhance nutrient uptake, improve soil structure, and suppress plant pathogens. Understanding the underlying mechanisms governing these advantages and their interactions with different crop species is pivotal for harnessing their full potential in sustainable agriculture.

2. Overview of Mortierella Species

Mortierella species, belonging to the subphylum Mortierellomycotina, are a diverse group of fungi that have garnered attention for their mutualistic associations with plants and their potential contributions to sustainable agriculture [6]. In this section, we will delve into the taxonomy, distribution, and general characteristics of Mortierella species, shedding light on their significance in agricultural ecosystems.

2.1.Taxonomy and Classification

Mortierella is a polyphyletic genus, which means that it includes species that do not share a common ancestor [7]. Taxonomically, Mortierella species fall within the Mortierellaceae family and the Mortierellales order. The taxonomy of Mortierella has undergone revisions to better reflect its evolutionary relationships, thanks to advances in molecular biology techniques.

Molecular phylogenetic studies have helped elucidate the evolutionary history of Mortierella species. They have been classified into various clades, each representing a distinct lineage within the genus [8]. These clades include the Mortierella elongata clade, Mortierella alpina clade, and Mortierella isabellina clade, among others.

2.2.Distribution and Habitat

Mortierella species exhibit a remarkable adaptability to different environmental conditions, which is reflected in their widespread distribution. They have been found in diverse habitats, ranging from soils to decaying organic matter and even extreme environments such as Antarctica [9,10].

One of the key ecological roles of Mortierella species is their involvement in the decomposition of organic matter. They contribute to the breakdown of complex organic compounds, releasing nutrients into the soil that are essential for plant growth [11]. This decomposition process is crucial for nutrient cycling in ecosystems.

2.3.General Characteristics

Mortierella species are typically characterized by their filamentous hyphae and sporangia. Unlike some other fungi, they do not form septa in their hyphae, leading to a multinucleate, coenocytic appearance. Their asexual reproduction occurs through the formation of sporangia, which release sporangiospores into the environment [12].

In addition to their role as decomposers, Mortierella species have gained recognition for their ability to form mutualistic associations with various plant species. These associations involve the establishment of mycorrhizal relationships, where the fungus colonizes the plant roots and facilitates nutrient exchange.

2.4.Importance in Soil Ecosystems

Mortierella species are integral components of soil ecosystems. Their ability to decompose organic matter contributes to the recycling of nutrients in the soil, making them available for plant uptake [11]. This nutrient cycling is essential for maintaining soil fertility and promoting plant growth.

Furthermore, Mortierella species play a crucial role in mycorrhizal associations with plants. Mycorrhizal fungi, including Mortierella spp., form symbiotic relationships with plant roots, enhancing nutrient uptake and overall plant health [13]. These associations are particularly beneficial in nutrient-poor soils.

Mortierella species also contribute to the suppression of soil-borne pathogens. Their presence in the soil can lead to the production of antifungal compounds and competition for resources, reducing the prevalence of harmful pathogens [14].

2.5.Significance in Agriculture

The agricultural sector has shown growing interest in harnessing the potential of Mortierella species to enhance crop productivity and sustainability. These fungi have the capacity to improve soil structure, increase nutrient availability, and suppress plant diseases [15].

Mortierella species' adaptability to a wide range of soil types and environmental conditions makes them attractive candidates for applications in agriculture [16]. They have been explored as bioinoculants, where they are introduced to agricultural soils to establish mycorrhizal associations with crop plants [17]. Additionally, Mortierella-based strategies have the potential to reduce the reliance on chemical fertilizers and pesticides, aligning with the principles of sustainable agriculture [18]. Their contributions to nutrient cycling and disease suppression can lead to improved crop yields and reduced environmental impacts.

Mortierella species, with their taxonomic diversity, widespread distribution, and crucial roles in soil ecosystems, hold significant promise in agriculture. Their capacity to form mutualistic associations with plants, enhance nutrient cycling, and suppress soil-borne pathogens underscores their potential as beneficial fungi for sustainable agricultural practices. Understanding the taxonomy, distribution, and general characteristics of Mortierella species is foundational to harnessing their full potential in enhancing plant growth in agricultural soils.

3. Beneficial Effects of Mortierella Species on Plant Growth

Mortierella species have gained prominence in agriculture due to their remarkable capacity to enhance plant growth and improve overall crop productivity. Their beneficial effects on plant growth stem from their ability to form mutualistic associations with plants and influence various physiological and biochemical processes. In this section, we will explore in detail the mechanisms underlying these beneficial effects and their significance in sustainable agriculture.

3.1.Promotion of Plant Growth

One of the primary benefits associated with Mortierella species is their role in promoting plant growth. These fungi establish mutualistic relationships with plants, particularly through mycorrhizal associations. Mycorrhizal fungi, including Mortierella spp., play a pivotal role in enhancing nutrient uptake by plants [19]. This enhanced nutrient acquisition leads to improved plant growth and vigor.

Mortierella species' mycorrhizal associations involve the colonization of plant roots by fungal hyphae. This extensive hyphal network extends into the surrounding soil, increasing the surface area available for nutrient absorption [20]. As a result, plants are better equipped to access essential nutrients such as phosphorus, nitrogen, and micronutrients.

3.2. Mechanisms of Action

Mortierella species employ various mechanisms to promote plant growth:

a. **Nutrient Cycling**: These fungi actively participate in nutrient cycling within the soil. Their hyphal networks scavenge for nutrients in the soil, contributing to the release of organic matter-bound nutrients, which are then made available to plants [21].

b. **Hormonal Regulation**: Mortierella species have been found to influence plant growth and development through the regulation of plant hormones. They can modulate the levels of important hormones such as auxins and gibberellins, which are involved in processes like root elongation and overall plant growth [22].

c. **Biocontrol**: Another valuable aspect of Mortierella species is their biocontrol potential.

They can suppress soil-borne pathogens through various mechanisms, including competition for resources and the production of antifungal compounds [23]. This biocontrol capability helps protect plants from diseases that can hamper their growth.

3.3.Comparison with Other Mycorrhizal Fungi

Mortierella species offer distinct advantages when compared to other mycorrhizal fungi. While arbuscular mycorrhizal fungi (AMF) are widely studied and utilized in agriculture, Mortierella spp. stand out due to their adaptability and ability to thrive in a broader range of soil conditions [24].

AMF are known to be highly beneficial in improving plant nutrient uptake, but their effectiveness can be limited by factors such as soil pH and temperature. In contrast, Mortierella species have demonstrated adaptability to both acidic and alkaline soils, making them valuable contributors to sustainable agriculture across diverse soil types [25].

Furthermore, Mortierella species have shown unique potential in enhancing plant growth through hormonal regulation and biocontrol mechanisms, offering additional benefits beyond nutrient uptake [26].

3.4.Field Studies and Experimental Evidence

The beneficial effects of Mortierella species on plant growth have been substantiated by numerous field studies and experiments. These studies have demonstrated increased crop yields and improved crop quality in the presence of these fungi.

For example, in a study conducted in agricultural fields, the inoculation of Mortierella species led to significant improvements in crop yield, particularly in nutrient-poor soils [27]. Similar findings have been reported in experiments with various crop species, including cereals, legumes, and vegetables [28].

Additionally, the use of Mortierella-based bioinoculants has gained traction as a sustainable agricultural practice. These bioinoculants, containing Mortierella species, are applied to agricultural soils to establish mycorrhizal associations with crop plants, ultimately leading to enhanced nutrient uptake and improved plant growth [29].

3.5.Impact on Crop Yield and Quality

The presence of Mortierella species in agricultural soils has a direct impact on crop yield and quality. By improving nutrient uptake, these fungi contribute to increased biomass production and larger harvests. This is particularly significant in regions with nutrient-depleted soils, where Mortierella-based strategies can help alleviate nutrient deficiencies and boost crop productivity [30].

Furthermore, the enhanced resistance to soil-borne pathogens provided by Mortierella species contributes to improved crop quality. Plants grown in the presence of these fungi are less susceptible to diseases, resulting in healthier and more marketable produce [31].

4. Interaction of Mortierella Species with Agricultural Crops

Understanding the interaction between Mortierella species and agricultural crops is crucial for harnessing the full potential of these beneficial fungi in sustainable agriculture. Mortierella spp. have demonstrated their ability to establish mycorrhizal associations with various crop species, leading to improved nutrient uptake, disease resistance, and overall crop performance. In this section, we will delve into the specifics of how Mortierella species interact with agricultural crops and their implications for crop production.

4.1.Compatibility with Different Crop Species

Mortierella species have exhibited a broad spectrum of compatibility with various agricultural crops. These fungi are known to

establish mycorrhizal associations with diverse plant families, including cereals (e.g., wheat, maize), legumes (e.g., soybeans, peas), vegetables (e.g., tomatoes, lettuce), and fruit trees (e.g., apple, citrus) [32,33].

The ability of Mortierella species to interact with a wide range of crop species underscores their versatility and potential applicability in different agricultural settings. Farmers can explore the use of these fungi across multiple crops to enhance nutrient uptake and improve crop yields.

4.2.Mycorrhizal Associations and Nutrient Uptake

The key mechanism underlying the interaction of Mortierella species with agricultural crops is the formation of mycorrhizal associations. These associations involve the colonization of crop plant roots by Mortierella hyphae, which extend into the surrounding soil [34].

Within the mycorrhizal association, Mortierella species play a pivotal role in nutrient uptake. Their extensive hyphal networks effectively scavenge the soil for nutrients, increasing the surface area for nutrient absorption. This results in improved access to essential elements such as phosphorus, nitrogen, and micronutrients [35].

The enhanced nutrient uptake facilitated by Mortierella mycorrhizal associations has been demonstrated in various crops. Studies have shown increased nutrient concentrations in plant tissues, leading to enhanced plant growth and crop yield [36]. This nutrient-driven growth improvement is especially valuable in nutrient-deficient soils.

4.3.Disease Suppression

Beyond nutrient uptake, Mortierella species offer protection to agricultural crops by suppressing soil-borne pathogens. Their presence in the soil can lead to the production of antifungal compounds and competition for resources with harmful pathogens [37].

This biocontrol capability contributes to disease resistance in crops and reduces the need for chemical pesticides. Farmers adopting Mortierella-based strategies can benefit from decreased disease incidence and improved crop health [38].

4.4. Field Studies and Practical Applications

The interaction between Mortierella species and agricultural crops has been extensively studied in field experiments. These studies have yielded promising results, demonstrating the positive impact of Mortierella mycorrhizal associations on crop production.

For example, in field trials with crops like maize and soybeans, the inoculation of Mortierella species led to significant increases in crop yield [39]. These findings highlight the practical applications of Mortierella-based bioinoculants in real-world agricultural scenarios.

4.5.Environmental Considerations

The interaction of Mortierella species with agricultural crops also has environmental implications. By enhancing nutrient uptake and disease resistance, these fungi contribute to more efficient resource utilization and reduced environmental impacts.

Mortierella-based strategies align with the principles of sustainable agriculture by reducing the need for chemical fertilizers and pesticides. This can lead to decreased soil and water pollution and lower greenhouse gas emissions associated with fertilizer production and application.

Additionally, the improved soil structure resulting from Mortierella mycorrhizal associations contributes to better soil health and resilience, which is crucial for long-term sustainable agriculture [40].

4.6.Challenges and Considerations

While the interaction of Mortierella species with agricultural crops holds significant promise, there are also challenges to be addressed. These include the development of effective inoculation techniques, optimization of application strategies, and considerations for specific crop types and environmental conditions.

Research efforts are ongoing to refine the practical implementation of Mortierella-based strategies, ensuring that they are cost-effective and yield consistent results across different agricultural settings.

5. Application Strategies for Mortierella Species in Agriculture

The successful integration of Mortierella species into agricultural practices relies on effective application strategies that maximize their potential benefits. These strategies encompass the selection of suitable Mortierella strains, inoculation methods, timing, and considerations for specific crop types and environmental conditions. In this section, we will delve into the key application strategies for Mortierella species in agriculture and their implications for sustainable crop production.

5.1. Strain Selection

The first step in harnessing the benefits of Mortierella species in agriculture is the careful selection of suitable strains. Different Mortierella strains may exhibit varying levels of compatibility with specific crops and environmental conditions. Therefore, it is essential to identify and characterize strains that are well-suited to the target crop and soil type.

Strain selection should consider factors such as:

a. **Crop Compatibility**: Some Mortierella strains may have a stronger affinity for certain crop species. It is crucial to choose strains that are known to establish successful mycorrhizal associations with the target crops [41].

b. **Soil Compatibility**: Soil conditions, including pH, texture, and nutrient content, can influence the effectiveness of Mortierella inoculation. Strains adapted to the specific soil conditions should be prioritized [42].

c. **Environmental Resilience**: Mortierella strains that exhibit resilience to environmental stressors, such as drought or salinity, may be preferred for regions with challenging climatic conditions [43].

d. **Beneficial Traits**: Some Mortierella strains may possess additional beneficial traits, such as enhanced nutrient solubilization or disease suppression capabilities. These strains can offer added advantages in specific agricultural contexts [44].

5.2. Inoculation Methods

The choice of inoculation method is a critical aspect of Mortierella species application. Various methods can be employed to introduce these fungi into the soil and establish mycorrhizal associations with crop roots. Common inoculation methods include:

a. **Seed Coating**: Coating seeds with Mortierella spores or mycelium prior to planting is a convenient method for introducing the fungi to the crop. This allows for direct contact between the fungi and developing root systems [45].

b. **Soil Drenching**: Applying Mortierella inoculum directly to the soil around established crop plants is another effective method. This approach ensures that the fungi colonize the root zone and establish mycorrhizal associations [46].

c. **Root Dip**: Immersing seedling roots in a Mortierella inoculum suspension before transplanting them into the field can facilitate early colonization and mycorrhizal association development [47].

d. **Fertigation**: Incorporating Mortierella inoculum into irrigation systems, often in combination with nutrient solutions, can provide a consistent supply of the fungi to crops throughout the growing season [48].

The choice of inoculation method should consider factors such as crop type, planting density, and available resources. Each method has its advantages and may be more suitable for specific agricultural scenarios.

5.3. Timing and Frequency

Timing plays a crucial role in the success of Mortierella species application. Inoculation should be timed to coincide with the crop's growth stages that are most receptive to mycorrhizal colonization. Typically, early stages of plant growth, such as germination and

early seedling development, offer optimal conditions for mycorrhizal establishment [49]. Additionally, the frequency of inoculation may vary depending on factors like crop growth rate and the duration of the growing season. Some crops may benefit from multiple inoculation events, while others may require only a single application at the appropriate stage [50].

5.4. Crop-Specific Considerations

Different crops have distinct requirements and responses to mycorrhizal associations. Therefore, it is essential to tailor Mortierella species application strategies to specific crop types. For example:

a. **Cereals**: Cereal crops like wheat and maize often benefit from Mortierella mycorrhizal associations due to improved nutrient uptake and increased resistance to soil-borne pathogens. Application methods that ensure early colonization of young seedlings can be particularly effective [51].

b. **Legumes**: Leguminous crops such as soybeans and peas can form nitrogen-fixing symbioses with Mortierella species, leading to enhanced nitrogen availability in the soil. Inoculation strategies should prioritize early establishment of these beneficial associations [52].

c. **Vegetables**: Vegetable crops, including tomatoes and lettuce, may benefit from Mortierella mycorrhizal associations that improve nutrient uptake and water utilization. Inoculation methods should align with the growth stages and planting practices specific to each vegetable type [53].

5.5. Environmental Considerations

Environmental conditions, such as soil pH, temperature, and moisture levels, should be taken into account when planning Mortierella species application. These fungi may exhibit varying degrees of adaptability to different environmental factors, and selecting strains and application methods that align with local conditions is crucial for success [54].

Additionally, considerations for long-term sustainability should include monitoring the persistence and effectiveness of Mortierella mycorrhizal associations over multiple growing seasons. Understanding the dynamics of these associations in changing environmental conditions can inform ongoing application strategies [55].

6. Environmental and Ecological Implications of Using Mortierella Species in Agriculture

The utilization of Mortierella species in agriculture not only offers potential benefits for crop production but also carries important environmental and ecological implications. These implications encompass the promotion of sustainable farming practices, the enhancement of soil health, and the conservation of biodiversity. In this section, we will explore the multifaceted environmental and ecological aspects associated with the incorporation of Mortierella species in agriculture.

6.1. Promotion of Sustainable Agriculture

One of the foremost environmental implications of using Mortierella species in agriculture is the promotion of sustainable farming practices. Mortierella mycorrhizal associations enable crops to access nutrients more efficiently, reducing the need for synthetic fertilizers. This, in turn, mitigates the environmental impact associated with fertilizer production and application, including greenhouse gas emissions and water pollution [56].

Sustainable agriculture aims to balance the economic viability of crop production with environmental stewardship. The reduced reliance on chemical fertilizers aligns with this objective, contributing to the conservation of natural resources and the long-term sustainability of farming systems [57].

6.2.Enhancement of Soil Health

The introduction of Mortierella species into agricultural soils has a profound impact on soil health. These fungi are active participants in

nutrient cycling and organic matter decomposition, leading to improved soil structure and fertility [58]. As a result, the ecological implications extend beyond crop growth:

a. **Increased Soil Organic Matter**: Mortierella mycorrhizal associations contribute to the accumulation of soil organic matter. This organic matter enhances soil water retention, nutrient availability, and overall soil quality [59].

b. **Soil Erosion Reduction**: Improved soil structure and root development facilitated by Mortierella species help reduce soil erosion, a critical environmental concern. Stable soil structures prevent the loss of valuable topsoil and minimize sediment runoff into water bodies [60].

c. **Microbial Diversity**: The presence of Mortierella species can influence the composition of soil microbial communities. While they interact with various microorganisms, including bacteria and other fungi, they contribute to the overall microbial diversity and ecosystem stability [61].

6.3.Mitigation of Soil-Borne Pathogens

Mortierella species possess biocontrol capabilities, which have implications for the ecological balance within agricultural ecosystems. These fungi can suppress soil-borne pathogens through competition for resources and the production of antifungal compounds [62]. This biocontrol action not only protects crops but also influences the dynamics of soil microorganisms:

a. **Pathogen Suppression**: The ability of Mortierella species to suppress soil-borne pathogens reduces the reliance on chemical pesticides, contributing to a decrease in chemical residues in soils and water bodies [63].

b. **Microbial Interactions**: Mortierella's interactions with soil pathogens and other microorganisms influence the structure and functioning of soil microbial communities. These ecological interactions can have cascading effects on nutrient cycling and ecosystem stability [64].

6.4.Conservation of Beneficial Insects and Soil Fauna

The ecological implications of Mortierella species also extend to the conservation of beneficial insects and soil fauna. By reducing the use of chemical pesticides and promoting a healthier soil ecosystem, these fungi support the presence and diversity of beneficial organisms:

a. **Beneficial Insects**: Reduced pesticide application benefits pollinators and other beneficial insects, which play essential roles in crop pollination and pest control [65].

b. **Soil Fauna**: Healthy soil ecosystems with diverse microbial communities, including those influenced by Mortierella species, provide habitats and food sources for soil fauna such as earthworms, nematodes, and arthropods. These organisms contribute to nutrient cycling and soil aeration [66].

6.5.Climate Change Mitigation

The incorporation of Mortierella species in agriculture also has implications for climate change mitigation. Improved soil health, nutrient cycling, and reduced fertilizer usage contribute to:

a. **Reduced Greenhouse Gas Emissions**: The decrease in synthetic fertilizer application associated with Mortierella mycorrhizal associations leads to a reduction in nitrous oxide emissions, a potent greenhouse gas [67].

b. **Carbon Sequestration**: Enhanced soil organic matter accumulation promoted by Mortierella species contributes to carbon sequestration in agricultural soils. This helps mitigate atmospheric carbon dioxide levels, a key driver of climate change [68].

6.6.Biodiversity Conservation

The presence of Mortierella species in agricultural soils can have indirect implications for biodiversity conservation. Sustainable farming practices that promote soil health and reduce environmental impact are more

compatible with maintaining biodiversity in agricultural landscapes:

a. **Habitat Preservation**: Reduced pesticide use and enhanced soil health create a more hospitable environment for native flora and fauna in and around agricultural fields [69].

b. **Biodiversity Corridors**: The adoption of sustainable practices, including Mortierella-based strategies, can facilitate the creation of biodiversity corridors, allowing for the movement of species and gene flow between fragmented habitats [70].

7. Conclusion

In the pursuit of sustainable agriculture, the integration of Mortierella species stands as a beacon of hope, offering a harmonious alliance between crop productivity and ecological well-being. This review has unveiled the multifaceted dimensions of Mortierella's role in enhancing plant growth in agricultural soils, shedding light on its potential applications and far-reaching implications.

Mortierella species, residing within the intricate tapestry of the soil ecosystem, emerge as steadfast allies to agriculture. Their capacity to form mutualistic associations with a diverse array of crop species transcends boundaries, demonstrating remarkable versatility. These alliances result in a symphony of benefits for both plants and the soil they call home.

Mortierella mycorrhizal associations, grounded in nutrient uptake, lay the foundation for crop prosperity. The fungi's ability to scavenge the soil for essential elements and transfer them to crops fuels growth and amplifies yields. Moreover, they wield the sword of biocontrol, warding off soil-borne pathogens and diminishing the reliance on chemical pesticides. Field studies have confirmed the tangible rewards of Mortierella-based strategies, showcasing enhanced crop performance and productivity. Yet, these advantages are not confined to crop roots alone; they reverberate through the soil ecosystem, reshaping its dynamics. Soil health flourishes as organic matter accumulates, erosion diminishes, and microbial diversity thrives.

The environmental and ecological implications of Mortierella's presence are profound. Sustainable agriculture finds an ally in Mortierella, as reduced fertilizer use and greenhouse gas emissions embody environmental stewardship. Soil health is revitalized, nurturing biodiversity and conserving beneficial insects. The quest for climate change mitigation finds an ally, with Mortierella aiding in carbon sequestration.

As the agricultural landscape evolves to address the pressing challenges of food security and environmental sustainability, the incorporation of Mortierella species emerges as an emblem of hope. It embodies the reconciliation of human needs with ecological balance, forging a path towards a more harmonious coexistence with the planet.

In the future, Mortierella species have the potential to play an even more significant role in sustainable agriculture. Further research into strain selection, application techniques, and the optimization of ecological interactions will refine our understanding and harness their full potential. As the journey continues, the alliance between Mortierella species and agriculture promises to flourish, forging a path towards a more sustainable and prosperous future.

The curtain falls on this review, leaving behind the resonance of Mortierella's silent symphony in agricultural soils, a testament to the potential of nature's collaborations in our quest for a sustainable world.

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