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Strategies to Optimize Dryland Farming Models for Enhancing Root Growth and Rhizosphere Microbial Functions in Hybrid Rice

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Abstract This feature review revealed several key findings. First, the diversity and functionality of rhizosphere microbial communities were significantly influenced by the rice genotype and soil type. Enhanced root traits, such as increased root biomass and root exudates, were found to promote beneficial microbial populations, including nitrogen-fixing bacteria and methanotrophs, which in turn improved plant growth and reduced methane emissions. The sequential inoculation of beneficial microbes, such as *Azotobacter vinelandii* and *Serendipita indica*, further augmented rice growth by enhancing root-shoot biomass and chlorophyll content. Additionally, the study demonstrated that hybrid rice cultivars could recruit specific rhizosphere microbiomes that facilitated better nutrient mineralization and reduced nutrient losses, thereby improving yield. This review underscore the importance of optimizing root traits and rhizosphere microbial functions to enhance the productivity and sustainability of hybrid rice in dryland farming systems. By leveraging the synergistic interactions between roots and rhizosphere microbes, it is possible to develop more resilient and efficient farming models that can contribute to global food security and environmental sustainability.

Keywords Dryland farming; Hybrid rice; Root growth; Rhizosphere microbial functions; Nitrogen-fixing bacteria; Methanotrophs; Crop productivity; Sustainable agriculture

1 Introduction

Dryland farming, a method of cultivating crops in regions with rainfed or limited water availability, is crucial for ensuring food security in arid and semi-arid regions. This agricultural practice relies on efficient water use and soil management techniques to maximize crop yield under water-scarce conditions. The importance of dryland farming is underscored by its potential to sustain agricultural productivity in the face of climate change, which is expected to exacerbate water scarcity issues globally (Bhattacharyya et al., 2021). In particular, the cultivation of hybrid rice and upland rice in dryland conditions presents unique challenges and opportunities for enhancing root growth and rhizosphere microbial functions, which are vital for nutrient uptake and overall plant health (Zhang et al., 2019; Bauw et al., 2020).

Rice cultivation in dryland environments faces several challenges, primarily due to the crop's high water requirements and sensitivity to water stress. One of the major issues is the inhibition of plant growth caused by the production of stress ethylene under decreased soil water availability (Belimov et al., 2009). Additionally, the interaction between water and phosphorus (P) availability is critical, as both are often limited in dryland conditions. Effective root system architecture and the presence of beneficial rhizosphere microbial communities are essential for optimizing water and nutrient uptake (Zhang et al., 2019; Bauw et al., 2020). Furthermore, the variability in microbial community composition and function under different water regimes adds another layer of complexity to managing dryland rice cultivation (Lu et al., 2018; Bhattacharyya et al., 2021).

This review aims to explore strategies to optimize dryland farming models specifically for enhancing root growth and rhizosphere microbial functions in hybrid rice, examine the role of rhizosphere bacteria, such as those containing 1-aminocyclopropane-1-carboxylate (ACC) deaminase, in mitigating the negative effects of water stress on rice plants, analyze the impact of different irrigation schemes and phosphorus application levels on root architecture and microbial community dynamics, and investigate the interactions between plant roots and microbial communities under water stress conditions, focusing on how these interactions can be leveraged to improve drought tolerance and nutrient uptake.

By addressing these objectives, we hope to provide a comprehensive understanding of the mechanisms underlying root and rhizosphere microbial function optimization in dryland farming systems, ultimately contributing to the development of more resilient and sustainable agricultural practices.

2 Overview of Hybrid Rice

2.1 Characteristics and advantages

Hybrid rice , intra- and inter-subspecies of *Oryza sativa*, is known for its superior yield and adaptability to various environmental conditions. This rice variety combines the desirable traits of traditional rice with the hybrid vigor seen in other rice subspecies, resulting in enhanced growth and productivity. The hybridization process has led to improved root systems and increased resistance to environmental stresses, which are crucial for optimizing dryland farming models (Xu et al., 2020). Additionally, hybrid rice exhibits a robust rhizosphere microbial community that plays a significant role in nutrient cycling and plant health, further contributing to its advantages over other rice varieties (Ding et al., 2019; Chen et al., 2022).

2.2 Current cultivation practices

Current cultivation practices for rice involve a combination of traditional and modern agricultural techniques. These practices include the use of chemical fertilizers, organic supplements like seaweed extract, and optimized irrigation schemes to enhance soil nutrient levels and microbial diversity (Zhang et al., 2019; Chen et al., 2022). The application of seaweed extract, for instance, has been shown to improve the rhizosphere bacterial community, leading to better nutrient availability and increased rice yield (Chen et al., 2022). Moreover, the integration of frequently alternate wetting and drying (FAWD) irrigation regimes with reduced phosphorus doses has been found to maintain grain yield while enhancing water and phosphorus use efficiency (Zhang et al., 2019; Hussain et al., 2022). These practices are tailored to maximize the growth potential of hybrid rice under varying agricultural conditions.

2.3 Performance under different agricultural conditions

Hybrid rice demonstrates remarkable performance under diverse agricultural conditions, including varying soil types and climatic environments. Studies have shown that the root-associated microbial communities of rice varieties including hybrid rice are significantly influenced by soil type, which in turn affects plant growth and yield (Xu et al., 2020; Xiong et al., 2021). For instance, the presence of beneficial microbes such as *Azotobacter vinelandii* and *Serendipita indica* has been found to augment rice growth by enhancing root-shoot biomass and chlorophyll content (Dabral et al., 2020; Hussain et al., 2022). Additionally, the rice genotype plays a crucial role in recruiting specific rhizosphere microbiomes that contribute to nutrient mineralization and reduced nutrient losses, thereby improving overall yield (Xu et al., 2020; Xiong et al., 2021). These findings underscore the adaptability and resilience of hybrid rice, making it a suitable candidate for optimizing dryland farming models.

By leveraging the unique characteristics and advantages of hybrid rice, along with tailored cultivation practices and an understanding of its performance under different agricultural conditions, researchers and farmers can enhance root growth and rhizosphere microbial functions, ultimately leading to improved crop productivity and sustainability.

3 Dryland Farming Models

3.1 Definition and types of dryland farming

Dryland farming refers to agricultural practices that rely on natural rainfall rather than irrigation. This method is particularly important in regions where water resources are scarce. There are several types of dryland farming, including:

Rainfed Agriculture: This type relies solely on rainfall for water. It is common in semi-arid regions where irrigation is not feasible (Mavrodi et al., 2018; Zhang et al., 2019).

Conservation Agriculture: This approach includes practices like minimal soil disturbance, crop rotation, and maintaining soil cover to enhance water retention and soil health (Lu et al., 2018; Zhang et al., 2019).

Agroforestry: Integrating trees and shrubs into crop and livestock systems to improve biodiversity, soil structure, and water use efficiency (Lu et al., 2018; Hakim et al., 2021).

3.2 Comparison of dryland and traditional irrigated farming

Dryland farming and traditional irrigated farming differ significantly in terms of water use, crop yield, and soil health:

Water Use: Dryland farming relies on rainfall, making it more sustainable in water-scarce regions. In contrast, traditional irrigated farming depends on consistent water supply from irrigation systems, which can deplete water resources (Mavrodi et al., 2018; Zhang et al., 2019).

Crop Yield: While irrigated farming generally results in higher yields due to controlled water supply, dryland farming can be optimized through practices like frequently alternate wetting and drying (FAWD) to maintain yields without excessive water use (Mavrodi et al., 2018; Zhang et al., 2019).

Soil Health: Dryland farming often promotes better soil health through practices like crop rotation and reduced tillage, which enhance microbial activity and soil structure. In contrast, traditional irrigated farming can lead to soil degradation and salinization if not managed properly (Lu et al., 2018; Schlatter et al., 2019; Hakim et al., 2021).

3.3 Implementation of dryland farming in rice cultivation

Implementing dryland farming in rice cultivation involves several strategies to optimize root growth and rhizosphere microbial functions:

Irrigation Management: Techniques like FAWD can be used to optimize water use efficiency and maintain grain yield. This method also enhances the abundance of beneficial rhizosphere bacteria, which aid in nutrient uptake (Xu et al., 2019; Zhang et al., 2019).

Microbial Inoculation: Introducing plant growth-promoting rhizobacteria (PGPR) and beneficial fungi like *Piriformospora indica* can enhance root growth and rhizosheath formation, improving drought resistance and nutrient uptake in rice (Hakim et al., 2021; Xu et al., 2021; Hussain et al., 2022).

Soil Amendments: Applying organic matter and phosphorus fertilizers in a controlled manner can improve soil fertility and support a healthy microbial community, which is crucial for sustainable rice production in dryland conditions (Ding et al., 2019; Zhang et al., 2019).

By adopting these strategies, dryland farming can be effectively implemented in rice cultivation, promoting sustainable agriculture and enhancing crop resilience to water scarcity.

4 Root Growth in Hybrid Rice

4.1 Root system architecture and function

The root system architecture (RSA) of hybrid rice plays a crucial role in nutrient and water uptake, which are essential for plant growth and productivity. The RSA includes various root types such as nodal roots, lateral roots, and root hairs, each contributing differently to the plant's overall function. For instance, lateral roots and growing root tips are particularly important for phosphate uptake, especially under varying water and phosphorus conditions (Bauw et al., 2020). Additionally, root exudates, which are chemical compounds secreted by roots, significantly influence the microbial community in the rhizosphere, thereby affecting root growth and function (Li et al., 2019; Upadhyay et al., 2022). An enormous diversity of microbes dwelling in root-associated zones, including endosphere (inside root), rhizoplane (root surface) and rhizosphere (soil surrounding the root surface), play essential roles in ecosystem functioning and plant health (Ding et al., 2019).

4.2 Factors affecting root growth in dryland conditions

Root growth in dryland conditions is influenced by several factors, including soil moisture, nutrient availability, and microbial interactions. Water stress and limited phosphorus availability can significantly alter root architecture, leading to changes in root mass, nodal root number, and lateral root types (Bauw et al., 2020). The PGPR utilize diverse mechanisms to enhance plant growth and development. These mechanisms include the production of phytohormones, solubilization of nutrients, biological nitrogen fixation, and protection of plants under conditions of biotic and abiotic stress (Hakim et al., 2021; Hussain et al., 2022; Grover et al., 2021) (Figure 1). Additionally, the rhizosphere effect, which is the influence of root exudates on microbial communities, plays a critical role in shaping the bacterial populations that support root growth under dryland conditions (Li et al., 2019).

4.3 Measuring and analyzing root growth

Measuring and analyzing root growth involves various techniques, including root imaging, soil sampling, and microbial community analysis. Advanced tools like 3D root system reconstruction models can predict the function of specific roots in terms of nutrient and water uptake under different environmental conditions (Bauw et al., 2020). Additionally, the use of 16S rRNA gene sequencing helps in understanding the diversity and activity of microbial communities in the rhizosphere, which are crucial for root health and growth (Li et al., 2019; Xu et al., 2019). These methods provide insights into how root traits interact with soil and microbial factors, thereby influencing overall plant performance.

By integrating these strategies, it is possible to optimize dryland farming models to enhance root growth and rhizosphere microbial functions in hybrid rice, ultimately leading to improved crop yields and sustainability.

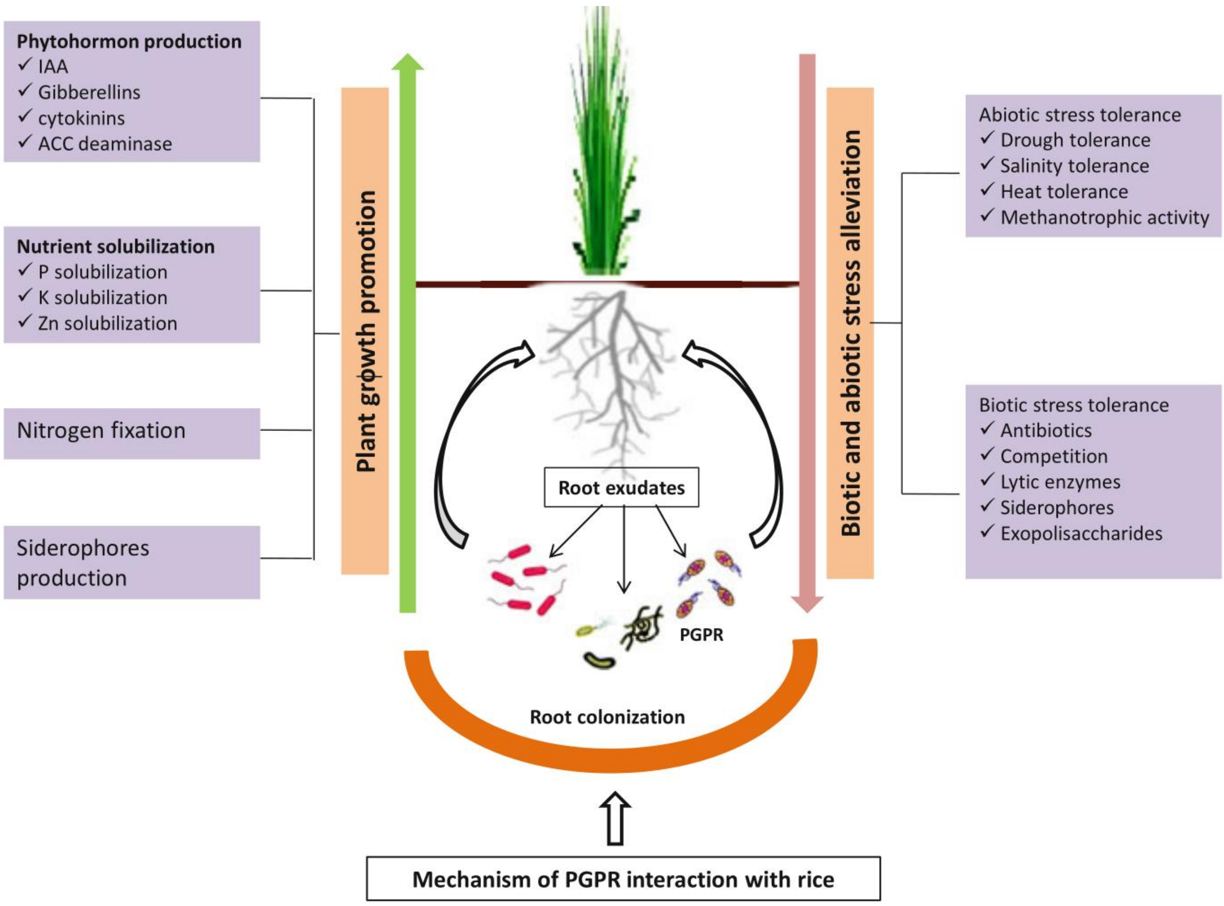

Figure 1 Rice-PGPR interaction and plant growth promoting attributes (Adopted from Hussain et al., 2022)

5 Rhizosphere microbial communities

5.1 Role of rhizosphere microbes in plant health and growth

Rhizosphere microbes play a crucial role in plant health and growth by facilitating nutrient acquisition, enhancing stress tolerance, and promoting overall plant vigor. These microbes, including bacteria and fungi, interact with plant roots to form a symbiotic relationship that benefits both parties. For instance, plant growth-promoting rhizobacteria (PGPR) such as *Azotobacter vinelandii* and *Serendipita indica* have been shown to significantly enhance rice growth by improving root-shoot biomass and chlorophyll content (Dabral et al., 2020). Additionally, the rhizosphere effect, driven by root exudates, shapes the microbial community, which in turn influences plant growth and productivity (Li et al., 2019). The presence of specific microbial taxa, such as Oxobacter and Lachnospiraceae, in the rhizosphere has been linked to improved plant health and biogeochemical cycling (Li et al., 2019).

5.2 Factors influencing rhizosphere microbial diversity

Several factors influence the diversity and composition of rhizosphere microbial communities. Soil type and plant genotype are primary determinants, with different soil types harboring distinct microbial communities (Xu et al., 2019). For example, the microbial communities in the rhizosphere of indica and japonica rice varieties differ significantly, influenced by both soil type and rice genotype (Xu et al., 2019). Additionally, root exudates, which include organic acids and other metabolites, play a significant role in shaping the microbial community by attracting specific microbial taxa (Li et al., 2019). Environmental conditions, such as moisture and nutrient availability, also impact microbial diversity. For instance, nitrogen and phosphorus fertilization have been shown to affect the richness and composition of rhizosphere bacterial communities in maize (Ujvári et al., 2023).

As one of the most important cultivated rice varieties in China, Yongyou 12 hybrid rice had similar endophytic microbiota to both *indica* and *japonica* rice cultivars (Feng et al., 2019). This result means that the hybrid not only exhibits strong heterosis but also shows a similar root bacterial community between *indica* and *japonica* rice types, which likely enhances its environ mental adaptation and defense potential, considering the im portance of microbiota to the host plant.

5.3 Methods for studying rhizosphere microbial communities

Various methods are employed to study rhizosphere microbial communities, each providing unique insights into microbial diversity and function. High-throughput sequencing techniques, such as 16S rRNA gene sequencing, are commonly used to characterize microbial communities at a taxonomic level (Xu et al., 2019). These methods allow for the identification of core microbial communities and the assessment of their functional potential. Metagenomic profiling further enhances our understanding by revealing the functional capabilities of microbial communities, such as nutrient cycling and stress response pathways (Lu et al., 2018). Additionally, techniques like polymerase chain reaction-denaturing gradient gel electrophoresis (PCR-DGGE) and amplicon sequencing are used to monitor changes in microbial community composition under different agricultural practices (Ujvári et al., 2023). Confocal microscopy and other imaging techniques provide visual insights into microbial colonization and interactions with plant roots (Dabral et al., 2020).

By understanding the role, influencing factors, and methods for studying rhizosphere microbial communities, researchers can develop strategies to optimize dryland farming models for enhancing root growth and rhizosphere microbial functions in hybrid rice. This knowledge is crucial for improving crop health, productivity, and sustainability in agricultural systems.

6 Interaction between Root Growth and Rhizosphere Microbes

6.1 Mechanisms of root-microbe interactions

The interaction between root growth and rhizosphere microbes is a complex and dynamic process that significantly influences plant health and productivity. Roots and their associated microbiomes co-evolve, forming intricate relationships that enhance plant fitness. Plants selectively recruit beneficial microbes through root exudates, which are chemical compounds secreted by roots into the rhizosphere. These exudates serve as signals and nutrients for microbes, fostering beneficial associations that aid in nutrient acquisition, stress tolerance, and disease resistance (Backer et al., 2018; Ding et al., 2019; Pantigoso et al., 2022). The assembly of root-associated microbial communities is primarily driven by deterministic processes, where specific microbes are consistently associated with particular plant traits and environmental conditions (Xu et al., 2019; Guo et al., 2021).

6.2 Impact of root exudates on microbial communities

Root exudates play a pivotal role in shaping the microbial communities in the rhizosphere. These exudates include a variety of organic compounds such as sugars, amino acids, and secondary metabolites that attract and sustain beneficial microbes. The composition and quantity of root exudates can vary depending on the plant species, developmental stage, and environmental conditions. For instance, rice plants have been shown to influence the structure of their rhizosphere microbial communities through specific exudates, which in turn affect nutrient cycling and plant health (Lu et al., 2018; Ding et al., 2019; Pantigoso et al., 2022). The selective recruitment of microbes by root exudates enhances the plant's ability to cope with abiotic stresses such as nutrient deficiency and drought (Backer et al., 2018; Khan et al., 2021).

6.3 Effects of microbial activity on root development

Microbial activity in the rhizosphere has profound effects on root development and overall plant growth. Beneficial microbes, such as plant growth-promoting rhizobacteria (PGPR) and mycorrhizal fungi, enhance root architecture by promoting root elongation, branching, and biomass accumulation. These microbes produce phytohormones, solubilize nutrients, and suppress soil-borne pathogens, thereby creating a conducive environment for root growth (Backer et al., 2018; Dabral et al., 2020; Shi et al., 2021) (Figure 2). For example, the synergistic inoculation of *Azotobacter vinelandii* and *Serendipita indica* has been shown to significantly enhance rice root and shoot biomass, demonstrating the potential of microbial inoculants in improving crop performance (Dabral et al., 2020). Additionally, the presence of a diverse and functional microbial community in the rhizosphere can enhance the plant's resistance to pathogens and improve nutrient uptake, further supporting robust root development (Lazcano et al., 2021; Hussain et al., 2022).

In summary, the interactions between root growth and rhizosphere microbes are mediated by complex mechanisms involving root exudates and microbial activity. These interactions play a crucial role in enhancing plant growth, stress tolerance, and overall productivity, making them a key focus for optimizing dryland farming models for hybrid rice.

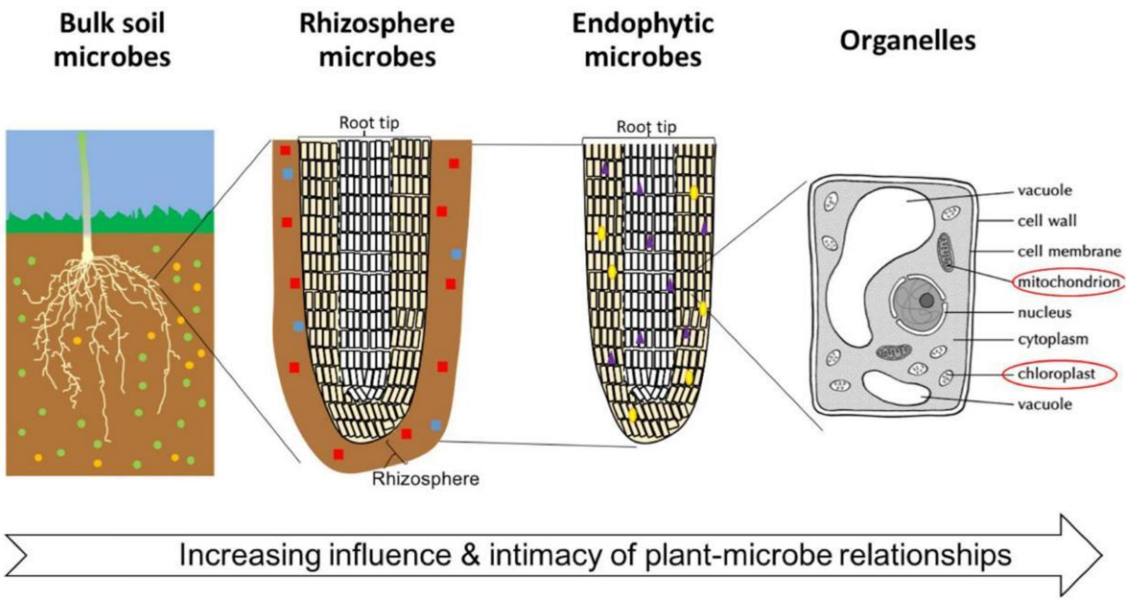

Figure 2 The degree of intimacy and influence of the plant-microbe interactions (Adopted from Backer et al., 2018)

Image caption: Microbes are represented by small colored (red, green, yellow, purple, and blue) shapes. Diversity and number of microbes is variable between soils, distance from plant roots, crop species, and plant tissue (Adopted from Backer et al., 2018)

7 Optimizing Dryland Farming Models

7.1 Soil moisture management

7.1.1 Mulching techniques

Mulching is a critical technique in dryland farming to conserve soil moisture, reduce soil erosion, and improve soil health. The application of rice straw as mulch has been shown to influence the microbial community structure in the rhizosphere, enhancing the abundance of beneficial bacteria such as Acidobacteria, which can improve soil health and plant growth (Otero-Jiménez et al., 2021). Additionally, mulching with organic materials can increase soil organic carbon content, which is essential for maintaining soil moisture and fertility (Tang et al., 2022).

7.1.2 Irrigation scheduling and methods

Optimizing irrigation scheduling and methods is vital for efficient water use in dryland farming. The frequently alternate wetting and drying (FAWD) irrigation regime has been found to maintain grain yield while enhancing the abundance of beneficial bacteria with acid phosphatase activity, which aids in phosphorus availability in the rhizosphere (Zhang et al., 2019). This method not only conserves water but also improves nutrient uptake and soil microbial functions.

7.2 Soil health improvement

7.2.1 Organic amendments and compost

The addition of organic amendments such as compost and rice straw significantly improves soil health by increasing soil organic matter, nutrient content, and microbial activity (Ayangbenro et al., 2022; Tang et al., 2022). Organic amendments enhance soil structure, water holding capacity, and stimulate the microbial community, leading to improved plant growth and resilience against stress (Ayangbenro et al., 2022; Tang et al., 2022).

7.2.2 Cover crops and crop rotation

Implementing cover crops and crop rotation is an effective strategy to improve soil health and reduce soil degradation. These practices enhance soil organic matter, improve soil structure, and increase microbial diversity and activity in the rhizosphere (Ayangbenro et al., 2022). Cover crops can also suppress weeds, reduce soil erosion, and enhance nutrient cycling, contributing to sustainable dryland farming systems.

7.3 Crop management practices

7.3.1 Plant density and spaCING

Optimizing plant density and spacing is crucial for maximizing root growth and resource use efficiency. Proper spacing ensures adequate light, water, and nutrient availability for each plant, reducing competition and promoting healthier root systems. This practice can lead to improved crop yields and better soil health (Tang et al., 2022).

7.3.2 Timing of planting and harvesting

The timing of planting and harvesting plays a significant role in crop performance and soil health. Planting at the optimal time ensures that crops can utilize available soil moisture and nutrients effectively, while timely harvesting prevents soil degradation and allows for the implementation of cover crops or other soil health improvement practices (Tang et al., 2022).

7.4 Use of beneficial microbes

7.4.1 inoculation with plant growth-promoting rhizobacteria (PGPR)

Inoculating crops with plant growth-promoting rhizobacteria (PGPR) can significantly enhance root growth and rhizosphere microbial functions. PGPR produce plant growth hormones, improve nutrient availability, and enhance plant stress tolerance, leading to better crop performance and soil health (Backer et al., 2018; Hakim et al., 2021; Hussain et al., 2022). These beneficial microbes can be an integral part of sustainable dryland farming models.

7.4.2 Mycorrhizal associations

Mycorrhizal fungi form symbiotic associations with plant roots, improving nutrient and water uptake, and enhancing soil structure and health. These associations are particularly beneficial in dryland farming, where water and nutrient availability are limited. Mycorrhizal fungi can increase root surface area, allowing plants to access more resources and improve overall plant health and productivity (Hakim et al., 2021).

By integrating these strategies, dryland farming models can be optimized to enhance root growth and rhizosphere microbial functions in hybrid rice, leading to improved crop yields and sustainable agricultural practices.

8 Case Studies and Practical Applications

8.1 Successful Implementation of Dryland Farming in Rice Cultivation

Dryland farming techniques have shown promising results in enhancing root growth and rhizosphere microbial functions in differrent rice varieties. For instance, the use of seaweed extract supplements in combination with reduced chemical fertilizers has been demonstrated to improve the diversity of rhizosphere bacteria, enhance soil nutrient levels, and increase rice yield and quality (Chen et al., 2022). Additionally, the synergistic inoculation of beneficial microbes such as *Azotobacter vinelandii* and *Serendipita indica* has been found to significantly augment rice growth, suggesting that microbial inoculants can be a valuable tool in dryland farming systems (Dabral et al., 2020). Furthermore, moderate soil drying (MSD) is a promising agricultural technique that can reduce water consumption and enhance rhizosheath formation promoting drought resistance in plants. The study (Xu et al.,2022) suggests that the interaction of the endophytic fungus *Piriformospora indica* with the native soil bacterium *Bacillus cereus* favors rice rhizosheath formation by auxins modulation in rice and microbes under MSD. This finding reveals a cooperative contribution of *P. indica* and native microbiota in rice rhizosheath formation under moderate soil drying, which is important for improving water use in agriculture (Figure 3).

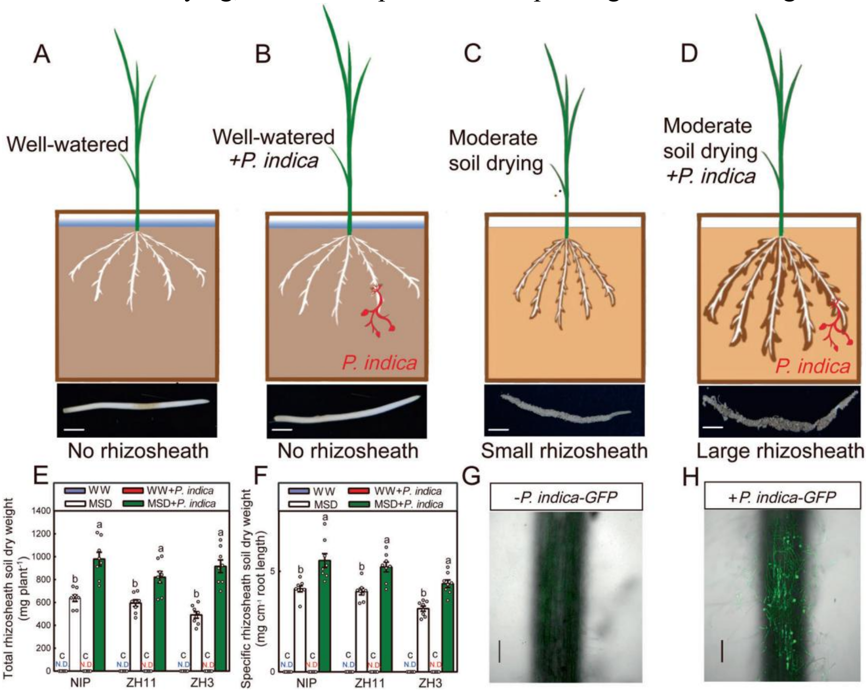

Figure 3 Rice rhizosheath formation is increased under moderate soil drying (MSD) with *P. indica* inoculation compared to MSD alone (Adopted from Xu et al., 2022)

Note: The non-inoculated and *P. indica*-inoculated rice seedlings (NIP rice) were cultured under well-watered (WW, A, B) and MSD (C, D) conditions. Rice seedlings (NIP rice) were able to form rhizosheath under MSD or MSD with *P. indica*-inoculation (MSD + *P. indica*), but not under WW or WW with *P. indica*-inoculation (WW + *P. indica*). Bar = 0.5 cm. The total rhizosheath soil dry weight (E) and specific rhizosheath soil dry weight (F) of three rice varieties (NIP, ZH11 and ZH3) under WW, WW + *P. indica*, MSD and MSD + *P. indica*. The specific rhizosheath dry weight was calculated as the total rhizosheath soil dry weight per plant (mg) divided by the total root length (cm). N.D. indicated that rhizosheath was not detectable. Data are the means ± SE (n = 8 replicates). Bars with different letters among different treatments are significantly different at $p < 0.05$ (ANOVA, Duncan's multiple range test). G, H Fluorescence microscopy of rice seedling (NIP rice) roots showing the presence of intracellular *P. indica* chlamydospores (spores are in green) in cortical cells using confocal microscopy with a superficial view. The image is an X- and Y-stack reconstruction. Rice roots without GFP-tagged *P. indica* (*P. indica*–GFP) inoculation were used as a control. Bar = 150 µm (Adopted from Xu et al., 2022)

8.2 Lessons learned from field trials

Field trials have provided valuable insights into the optimization of dryland farming models. One key lesson is the importance of managing irrigation and phosphorus application. Studies have shown that frequently alternate wetting and drying (FAWD) regimes, combined with optimized phosphorus application, can maintain grain yield while enhancing the abundance of beneficial rhizosphere bacteria (Zhang et al., 2019). Another important finding is the role of root traits in methane emissions. Stronger root systems with higher oxygen delivery and suitable root exudates can create a favorable habitat for methanotrophs, thereby reducing methane emissions in paddy fields (Chen et al., 2019).

8.3 Recommendations for farmers and agricultural practitioners

Based on the findings from various studies, several recommendations can be made for farmers and agricultural practitioners aiming to optimize dryland farming models for hybrid rice:

Microbial Inoculants: Utilize beneficial microbial inoculants such as *Azotobacter vinelandii* and *Serendipita indica* to enhance root growth and overall plant health (Dabral et al., 2020).

Seaweed Extracts: Incorporate seaweed extract supplements into fertilization regimes to improve rhizosphere bacterial diversity and soil nutrient levels, which can lead to increased rice yield and quality (Chen et al., 2022).

Irrigation Management: Implement frequently alternate wetting and drying (FAWD) irrigation regimes to optimize water and phosphorus use efficiency without sacrificing yield (Zhang et al., 2019).

Root Trait Enhancement: Focus on breeding or selecting rice varieties with strong root systems that can deliver higher oxygen levels to the rhizosphere, promoting beneficial microbial activity and reducing methane emissions (Chen et al., 2019).

Soil Type Consideration: Pay attention to soil type as it significantly influences the root-associated microbial community. Tailor farming practices to the specific soil conditions to maximize microbial benefits (Xu et al., 2019).

Phosphorus Application: Optimize phosphorus application levels to enhance rhizosphere microbial functions and improve plant growth (Zhang et al., 2019).

Monitoring and Adaptation: Continuously monitor soil and plant health, and be prepared to adapt farming practices based on observed outcomes and environmental conditions (Ding et al., 2019).

Sustainable Practices: Emphasize sustainable agricultural practices that minimize the use of synthetic fertilizers and agrochemicals, leveraging the benefits of plant growth-promoting rhizobacteria (PGPR) and other biostimulants (Backer et al., 2018).

By integrating these strategies, farmers can enhance root growth and rhizosphere microbial functions, leading to more resilient and productive hybrid rice cultivation under dryland farming conditions.

9 Future Research Directions

9.1 Knowledge gaps and challenges

Despite significant advancements in understanding the interactions between root growth, rhizosphere microbial functions, and hybrid rice, several knowledge gaps and challenges remain. One major challenge is the limited understanding of the specific microbial taxa and their functional roles in the rhizosphere of hybrid rice. While studies have identified core microbial communities and their potential benefits (Xu et al., 2019; Guo et al., 2021; Kumawat et al., 2021), the precise mechanisms through which these microbes enhance root growth and stress tolerance are not fully elucidated. Additionally, the influence of different soil types and environmental conditions on the rhizosphere microbiome and its functions needs further exploration (Ding et al., 2019; Li et al., 2019; Xu et al., 2019). Another challenge is the integration of multi-omics approaches to comprehensively analyze the interactions between plant roots and microbial communities, which can provide deeper insights into the molecular mechanisms underlying these interactions (Kumawat et al., 2021; Xiong et al., 2021).

9.2 Innovative techniques and technologies

To address these knowledge gaps, innovative techniques and technologies should be employed. Advanced metagenomics and metatranscriptomics can be utilized to identify and characterize the functional genes and pathways involved in root-microbe interactions (Lu et al., 2018; Xiong et al., 2021). Additionally, the use of high-throughput sequencing and bioinformatics tools can help in understanding the complex microbial networks and their dynamics in the rhizosphere (Li et al., 2019; Kumawat et al., 2021). Techniques such as stable isotope probing (SIP) and fluorescence in situ hybridization (FISH) can be used to track the activity and localization of specific microbial taxa in the rhizosphere (Zhang et al., 2019; Dabral et al., 2020). Furthermore, the development of synthetic microbial communities and their application in controlled environments can provide valuable insights into the functional roles of individual microbial species and their interactions with plant roots (Dabral et al., 2020; Guo et al., 2021).

9.3 Collaborative research and development

Collaborative research and development efforts are essential to advance our understanding and optimization of dryland farming models for hybrid rice. Interdisciplinary collaborations between microbiologists, plant scientists, agronomists, and data scientists can facilitate the integration of diverse expertise and technologies (Kumawat et al., 2021). Partnerships between academic institutions, industry, and farmers can promote the practical application of research findings and the development of sustainable farming practices (Kumawat et al., 2021; Zhang et al., 2019). Additionally, international collaborations can help in addressing the global challenges of food security and climate change by sharing knowledge and resources (Chen et al., 2019; Ding et al., 2019). Establishing long-term field trials and monitoring programs can provide valuable data on the effectiveness and sustainability of different farming practices and microbial inoculants (Chen et al., 2019; Zhang et al., 2019).

By addressing these knowledge gaps, employing innovative techniques, and fostering collaborative research, we can enhance root growth and rhizosphere microbial functions in hybrid rice, ultimately leading to improved crop productivity and sustainability in dryland farming systems.

10 Concluding Remarks

In conclusion, the optimization of dryland farming models for hybrid rice through the enhancement of root growth and rhizosphere microbial functions presents a promising avenue for sustainable agriculture. Future research should focus on the long-term effects of these strategies on soil health and crop productivity. Additionally, the development of tailored microbial inoculants and organic supplements that cater to specific hybrid rice variety and soil conditions could further enhance the effectiveness of these approaches. Policymakers and agricultural practitioners should consider integrating these findings into agricultural practices to promote sustainable and resilient farming systems. By leveraging the synergistic potential of plant-microbe interactions, it is possible to achieve higher rice yields, improved soil health, and reduced environmental impact, thereby contributing to global food security and sustainability.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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