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Improving Rice Yield under Direct Seeding through Synergistic Water and Fertilizer Management

Dengjun Liu [1,2]
1 Youhe Youmi Agricultural Development (Jiaxing) Co., Ltd., Pinghu, 314200, Zhejiang, China
2 Zhejiang Agronomist College, Hangzhou, 310021, Zhejiang, China
Corresponding email: 806972515@qq.com

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Abstract This study focuses on the role of integrated water and fertilizer management in improving yield, quality, and resource use efficiency in direct-seeded rice systems. The findings reveal that comprehensive practices combining Alternate Wetting and Drying (AWD) with Site-Specific Nutrient Management (SSNM), controlled-release fertilizers, and precise nitrogen management significantly enhance yield components, water productivity, and nitrogen use efficiency in direct-seeded rice. Simultaneously, these strategies reduce greenhouse gas emissions and nutrient losses, mitigating environmental impacts. Case studies further validate the practical effectiveness of these approaches, demonstrating the feasibility of achieving high yields and sustainability in direct-seeded rice systems. This study underscores the critical importance of water and fertilizer synergy in enhancing the productivity and sustainability of direct-seeded rice, aiming to provide actionable solutions for addressing global food security challenges under resource constraints and offering directions for sustainable rice production.

Keywords Direct-seeded rice (DSR); Water and fertilizer synergy; Precision nutrient management; Alternate wetting and drying (AWD); Sustainable rice production

1 Introduction

Direct-seeded rice (DSR) systems have emerged as a promising alternative to traditional transplanted rice due to their reduced labor and water requirements, which are critical in the face of increasing resource scarcity and labor shortages (Xu et al., 2019; Bhandari et al., 2020; Rathika et al., 2020). However, DSR systems often face challenges such as lower yields compared to transplanted rice, primarily due to issues like poor crop establishment, high weed infestation, and suboptimal nutrient management (Sandhu et al., 2021). Therefore, improving rice yield under DSR systems is crucial for ensuring food security and sustainability in rice production, especially in regions where water and labor are limiting factors (Xu et al., 2019; Bhandari et al., 2020).

Effective water and fertilizer management are pivotal in enhancing the productivity of DSR systems. Studies have shown that precision nitrogen management and optimized irrigation strategies can significantly improve grain yield, water productivity, and nutrient use efficiency in DSR (Kumar et al., 2019; Pratap et al., 2022). For instance, the integration of soil matric potential-based irrigation strategies with precise nitrogen application has been demonstrated to maximize yield while minimizing water input (Kumar et al., 2019). Additionally, the use of soil test-based fertilizer applications has been found to enhance nutrient uptake and yield, further highlighting the importance of synergistic management practices (Singh et al., 2021). These strategies not only improve yield but also contribute to better resource use efficiency and environmental sustainability (Kumar et al., 2019; Singh et al., 2021; Pratap et al., 2022).

This study investigates the synergistic effects of water and fertilizer management on improving rice yield under direct-seeded conditions. By exploring various management strategies, this study aims to identify optimal practices that enhance yield, resource use efficiency, and economic returns in DSR systems, and hopes that the findings are expected to provide valuable insights into developing sustainable and efficient rice production systems that can address the challenges posed by resource constraints and environmental concerns.

2 Direct-Seeding Systems in Rice

2.1 Characteristics of direct-seeding systems

Direct-seeding systems in rice cultivation have gained popularity due to their labor-saving benefits and adaptability to mechanization. This method involves sowing seeds directly into the field, bypassing the traditional transplanting stage. Direct seeding can be implemented in both wet and dry conditions, offering flexibility in water management. The system is known for its potential to reduce production costs and improve resource use efficiency, such as water and nitrogen, compared to traditional methods (Liu et al., 2014; Santiago - Arenas et al., 2021; Guo et al., 2022; Wu et al., 2023). According to our analysis of the 2024 rice trial data, compared to seedling transplanting (mechanized rice transplanting), direct seeding (drone broadcast seeding) resulted in a 33.3% increase in field mechanization costs and a 20% increase in seed costs. However, labor costs decreased by 78.8%, leading to an overall cost reduction of 29.5%.

2.2 Agronomic challenges in direct-seeding systems

Despite its advantages, direct-seeding systems face several agronomic challenges. One major issue is the management of nitrogen fertilizer, which is crucial for optimizing yield and nitrogen use efficiency (NUE). Inappropriate nitrogen management can lead to reduced seedling emergence and lower yields (Ma et al., 2023). Additionally, direct-seeded rice is more susceptible to weed competition and requires precise water management to prevent water stress or excessive water use (Santiago - Arenas et al., 2021; Fu et al., 2023). The system also demands careful attention to soil health and structure, as these factors significantly influence root development and nutrient uptake (Guo et al., 2022).

2.3 Role of water and fertilizer in yield optimization

Water and fertilizer management play a pivotal role in optimizing yields in direct-seeding systems. Synergistic management of these inputs can enhance rice yield, quality, and resource use efficiency. For instance, controlled-release fertilizers combined with appropriate irrigation strategies can reduce nitrogen losses and improve NUE, leading to higher yields (Wu et al., 2023; Zhu et al., 2024b). Studies have shown that optimizing the timing and method of nitrogen application, such as transferring a portion of nitrogen from basal to tillering stages, can significantly increase yield and improve plant development (Li et al., 2024; Zhu et al., 2024a). Moreover, innovative irrigation methods, like alternate wetting and drying, have been found to save water while maintaining comparable yields to continuous flooding systems (Tao et al., 2015; Santiago - Arenas et al., 2021). These strategies highlight the importance of integrated water and fertilizer management in achieving sustainable and high-yielding direct-seeded rice systems.

3 Synergistic Water and Fertilizer Management

3.1 Water management strategies

Water management plays a pivotal role in rice cultivation, influencing both yield and resource efficiency. Several strategies have been identified to optimize water use. Alternate wetting and drying (AWD) has been shown to save 40%~44% more water compared to continuous flooding, while maintaining similar grain yields. AWD also enhances water productivity by 68% (Santiago - Arenas et al., 2021). Implementing a 30% water-saving irrigation strategy can significantly improve dry matter quality, yield, and nutrient absorption in dry direct-seeded rice. This approach enhances rice processing, appearance, and nutritional quality (Lu and Li, 2023). Wet-shallow irrigation reduces irrigation water use by 35.2% and increases irrigation water productivity by 42.0%~42.8%, thereby improving overall water productivity (Zhu et al., 2024a).

3.2 Fertilizer application techniques

Optimizing fertilizer application is essential for improving rice yield and nitrogen use efficiency (NUE). Combining controlled-release fertilizers with urea reduces nitrogen losses and enhances NUE and yield in wet direct-seeded rice (Wu et al., 2023). Transferring 20% of total nitrogen from basal to tillering stages significantly increases yield and improves nitrogen use efficiency in direct-seeded ratoon rice systems (Li et al., 2024). The use of bioorganic fertilizers, such as Jishiwang combined with conventional NPK, enhances soil fungal community diversity and increases rice yield (Guo et al., 2022).

3.3 Synergistic approaches

Integrating water and fertilizer management strategies can lead to synergistic effects, enhancing rice yield and quality. The combination of wet irrigation and optimized nitrogen application (e.g., 225 kg/ha) significantly improves photosynthetic efficiency, non-structural carbohydrate accumulation, and lodging resistance, leading to higher yields and better rice quality (Figure 1) (Zhu et al., 2024b). Simplified and nitrogen-reduced practices, which involve reduced nitrogen fertilizer and labor input, have been shown to increase grain yield and NUE by enhancing sink capacity, productive tillers, and biomass accumulation (Fu et al., 2023). Utilizing controlled-release nitrogen fertilizers in a one-time application can balance yield, quality, and economic benefits, reducing fertilization frequency while maintaining high yield and quality (Cheng et al., 2023).

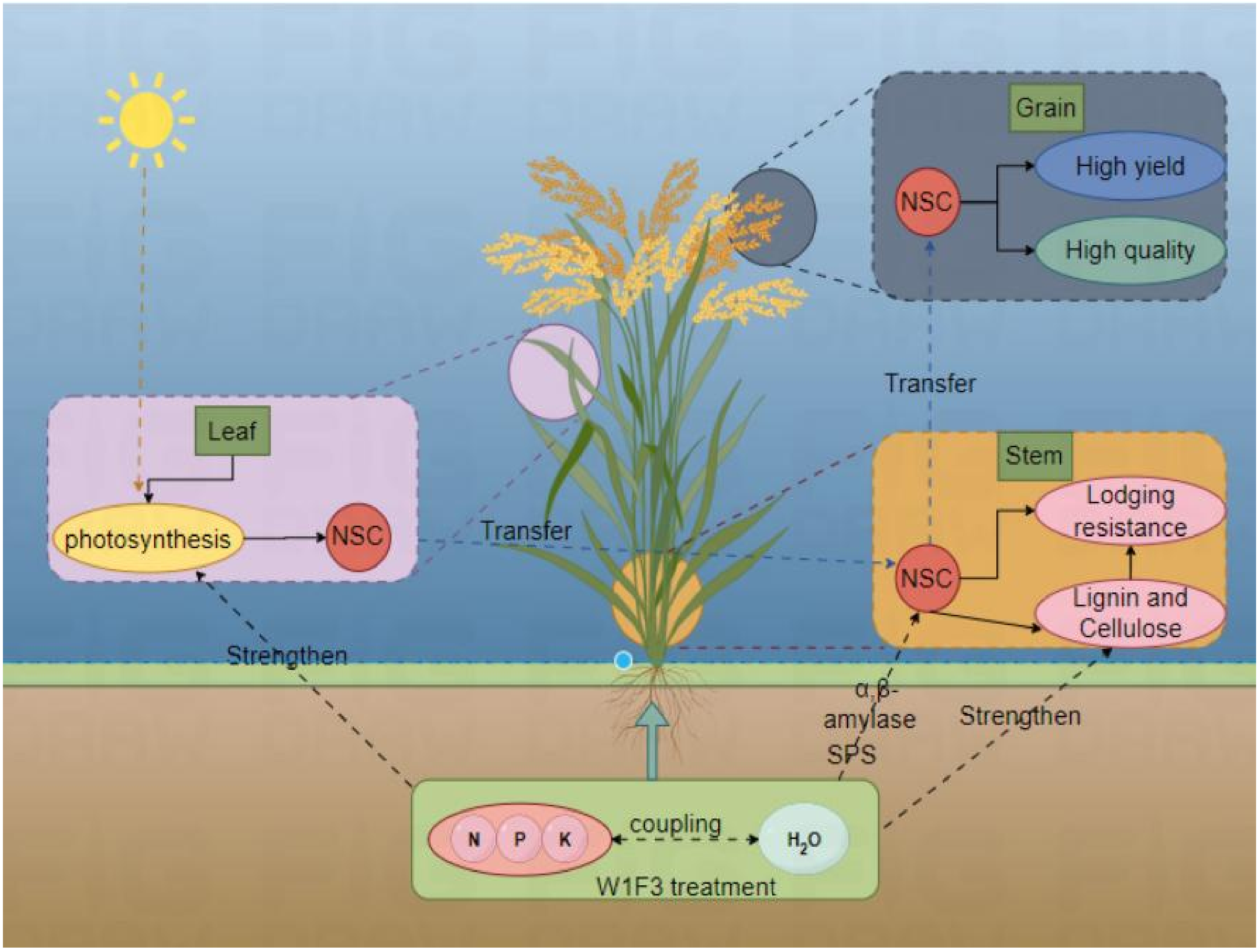

Figure 1 Synergistic regulation of yield, quality, and lodging resistance by water and fertilizer management (Adopted from Zhu et al., 2024b)

4 Physiological Responses of Rice to Water and Nutrient Synergy

4.1 Growth dynamics and biomass accumulation

The synergy between water and nutrient management significantly influences the growth dynamics and biomass accumulation in rice. Optimized water and fertilizer management, such as the W1F3 treatment, enhances photosynthetic efficiency and non-structural carbohydrate (NSC) accumulation, which are crucial for robust growth and high yield (Zhu et al., 2024b). Additionally, treatments like W1N2 have been shown to increase grain biomass accumulation by improving root oxidation activity and hormone balance, which supports effective panicle number and seed-setting performance (Zhao et al., 2023). The application of controlled-release fertilizers also extends the duration of rapid nitrogen growth, enhancing nitrogen accumulation and transport, which contributes to increased biomass and yield (Wu et al., 2023).

4.2 Stress tolerance

Water and nutrient synergy plays a vital role in enhancing rice's stress tolerance. The integration of water-saving irrigation techniques with nutrient management, such as the 30% water-saving irrigation combined with conditioners, improves rice's resilience during critical growth stages like tillering and grain filling (Lu and Li, 2023). This approach not only supports better growth under water-limited conditions but also enhances nutrient absorption, contributing to improved stress tolerance. Moreover, the use of optimized nitrogen management strategies, such as the N4 treatment, reduces ammonia volatilization and supports delayed senescence, which helps maintain higher leaf SPAD values and canopy photoassimilation, thereby enhancing stress tolerance (Ma et al., 2023).

4.3 Yield components

The synergistic management of water and nutrients significantly impacts the yield components of rice. For instance, the W1F3 treatment has been identified as optimal for increasing nitrogen uptake and improving the harvest index, leading to higher yields (Zhu et al., 2024a). Similarly, the use of controlled-release fertilizers combined with urea (CRBF+U) has been shown to improve the grain number per panicle, seed-setting rate, and actual yield by enhancing nitrogen use efficiency and reducing nitrogen losses (Wu et al., 2023). Additionally, integrated nutrient management strategies, such as combining organic and inorganic sources with biofertilizers, have been found to enhance yield attributes like panicle length and grain weight, ultimately boosting productivity and profitability (Table 1) (Kumar et al., 2023).

5 Environmental Implications of Water and Fertilizer Management

5.1 Water use efficiency and conservation

Water management strategies such as alternate wetting and drying (AWD) and optimized irrigation schedules have been shown to significantly improve water use efficiency in rice cultivation. For instance, AWD can save 40%~44% of water compared to continuous flooding, while maintaining similar grain yields (Santiago‑Arenas et al., 2021).

Additionally, the use of water-saving irrigation methods like “thin, shallow, wet, dry irrigation” can reduce irrigation water by 35.2% and increase water productivity by 42.0%~42.8% (Zhu et al., 2024a). These strategies not only conserve water but also enhance the sustainability of rice production systems. Through comparative experiments, we found that before rice seedlings reached a height of 5 cm, drone direct seeding required two fewer irrigation cycles and reduced water usage by 50% compared to mechanized transplanting, while the rice yield remained nearly the same.

5.2 Nutrient use efficiency and pollution reduction

Optimizing nitrogen (N) management is crucial for improving nutrient use efficiency and reducing environmental pollution. Precision nutrient management techniques, such as the use of Nutrient Expert® and SPAD meter-based N management, have been shown to save up to 27.1% of nitrogen while increasing grain yields and water productivity (Pratap et al., 2022). Moreover, reducing nitrogen application rates from 120 to 60 kg/ha can achieve desirable grain yields and water productivity, significantly lowering fertilizer input costs and environmental impact (Santiago‑Arenas et al., 2021). These practices help in minimizing nitrogen losses and reducing greenhouse gas emissions, such as nitrous oxide (N_2O) (Sadhukhan et al., 2023).

5.3 Ecosystem services

Water and fertilizer management also play a role in enhancing ecosystem services. The integration of organic fertilizers with conventional NPK fertilizers can improve soil health by enhancing the soil fungal community, which in turn supports higher rice yields (Guo et al., 2022). Additionally, improved water management practices can reduce methane (CH_4) emissions by 30%~34% and nitrous oxide emissions by 64%~66%, contributing to a lower greenhouse gas footprint (Islam et al., 2020). These practices not only support sustainable rice production but also contribute to broader environmental benefits by maintaining ecosystem balance and reducing pollution.

Table 1 Effect of integrated nutrient management on yield attributes of direct seeded rice under Rainfed conditions (Adopted from Kumar et al., 2023)

Treatment		Number of tillers		Panicle length (cm)	Panicle Weight (g)	Number of filled grains Panicle^{-1}	Total Number of grain spanicle $^{-1}$	Grain yield panicle^{-1} (g)	1000-grain weight (g)
		Productive tillers (m^{-2})	Unproductive tillers (m^{-2})						
T1	Control	274.33	54.00	19.13	2.40	45.00	54.66	0.92	20.63
T2	100% recommended dose of NPK through fertilizer (100 kg N+40 kg P_2O_5+ 40 kg K_2O/ha)	321.66	49.00	22.33	3.41	73.33	80.66	1.89	25.84
T3	100% RDN through compost	309.33	50.00	20.96	3.01	68.66	76.66	1.74	25.48
T4	50% RDN through fertilizer + 50% RDN through compost	317.66	49.33	21.10	3.23	69.66	77.33	1.80	25.91
T5	50% RDN through fertilizer + 25% RDN through compost	295.00	51.66	18.03	2.71	61.00	70.00	1.51	24.76
T6	25% RDN through fertilizer + 50% RDN through compost	287.00	52.00	17.9	2.63	60.33	69.66	1.48	24.67
T7	50% RDN through fertilizer + 25% RDN through compost + seed treated with Azotobacter @ 10 g/kg seed	304.00	50.33	19.53	2.96	66.66	74.66	1.69	25.40
T8	25% RDN through fertilizer + 50% RDN through compost + seed treated with Azotobacter @ 10 g/kg seed	298.33	51.33	19.43	2.92	65.66	73.33	1.66	25.33
T9	50% RDN through fertilizer + 50% RDN through compost + seed treated with Azotobacter @ 10 g/kg seed	340.66	46.66	23.57	3.76	75.33	82.33	2.01	26.69
SEm±	-	4.22	1.24	1.03	0.20	1.22	1.22	0.10	0.70
CD (5%)	-	12.67	3.74	3.09	0.61	3.66	3.67	0.30	2.33

6 Case Study

6.1 Case study 1: AWD and SSNM integration in Southeast Asia

The integration of Alternate Wetting and Drying (AWD) with Site-Specific Nutrient Management (SSNM) has shown promising results in Southeast Asia. This approach has been effective in reducing water inputs by 13.4% to 27.5% and surface runoff by 30.2% to 36.7% compared to conventional practices. Additionally, the combination of AWD and SSNM significantly reduced nitrogen (N) and phosphorus (P) losses via surface runoff by 39.4% to 47.6% and 46.1% to 48.3%, respectively, while maintaining high rice yields. This synergy not only enhances water and nutrient use efficiency but also mitigates environmental impacts, making it a sustainable practice for rice cultivation in the region (Liang et al., 2013; Liu et al., 2013).

6.2 Case study 2: precision nutrient management in India

In India, precision nutrient management has been implemented in zero-till direct-seeded rice systems, leading to improved productivity and environmental benefits. The use of soil-test-based NPK (STB-NPK) and Nutrient Expert® (NE-NPK) applications resulted in a 12% higher grain yield over the recommended dose of fertilizers. Moreover, NE-NPK increased agronomic efficiency of nitrogen (AEN) by 7% and phosphorus (AEP) by 35% compared to STB-NPK. This approach also significantly reduced nitrous oxide (N_2O) emissions by 49%, highlighting its potential to enhance nutrient use efficiency and reduce greenhouse gas emissions in rice production (Khurana et al., 2007; Sadhukhan et al., 2023).

6.3 Case Study 3: mechanized precision dry direct seeding technology for rice in China

In recent years, mechanized precision dry direct seeding technology has been tested, demonstrated, and promoted in China, particularly in areas where irrigation is inconvenient or water retention is poor. This technology eliminates the need for seedling cultivation, field soaking, and transplanting. Instead, it involves directly sowing an accurate amount of seeds into the field using machinery. As a simplified rice cultivation method, it reduces labor and time requirements, conserves water, lowers costs, and is well-suited for large-scale mechanized operations, ultimately enhancing cost efficiency, quality, and productivity in rice production (Wang et al., 2020).

According to our 2024 trial results, the total time required from seed preparation to field seeding (or transplanting) with precision dry direct seeding was only 2.5 days, which was 2.5 days shorter than mechanized direct seeding and 18 days shorter than mechanized transplanting, significantly reducing the planting duration. From a cost-saving perspective, precision dry direct seeding reduced costs by 56% compared to mechanized direct seeding and 101.6% compared to mechanized transplanting. Regarding seedling quality and weed incidence, the seedling quality of precision dry direct seeding was comparable to that of other methods. However, mechanized transplanting had slightly lower weed incidence and a slightly higher seedling establishment rate (Figure 2). At harvest, the thousand-grain weight for precision dry direct seeding was 24.6 g, which was higher than 21.6 g for mechanized direct seeding and 24.1 g for mechanized transplanting. In terms of final rice yield, precision dry direct seeding outperformed mechanized direct seeding by 5.10% and mechanized transplanting by 2.98%, demonstrating its potential as an efficient and cost-effective rice cultivation method.

Figure 2 Comparison of seedling quality in the field across three rice sowing methods
Image caption: a: Precision dry direct seeding; b: Mechanized direct seeding; c: Mechanized transplanting

6.4 Lessons learned from case studies

The case studies demonstrate that integrating advanced water management techniques like AWD with precision nutrient management strategies such as SSNM can significantly improve rice yield and resource-use efficiency. These practices not only enhance productivity but also contribute to environmental sustainability by reducing water usage and nutrient losses. The success of these strategies in different regions underscores the importance of tailoring agricultural practices to local conditions to achieve optimal results. The lessons learned emphasize the need for continued innovation and adaptation in rice cultivation to address the challenges of water scarcity and environmental degradation while ensuring food security (Khurana et al., 2007; Liang et al., 2013; Liu et al., 2013; Sadhukhan et al., 2023).

7 Technological Innovations in Water and Fertilizer Management

7.1 Smart irrigation systems

Smart irrigation systems, such as those utilizing sensors and the Internet of Things (IoT), have been identified as effective methods to enhance water use efficiency in rice farming. These systems allow for precise control of water application, reducing wastage and improving crop yield. However, the high cost of these technologies can be a barrier for small-scale farmers (Figure 3) (Mallareddy et al., 2023). Alternate wetting and drying (AWD) is another smart irrigation technique that has been shown to save water and maintain yields, while also reducing greenhouse gas emissions (Islam et al., 2020; Huang, 2024).

Figure 3 A smart irrigation device installed in the field (Adopted from Mallareddy et al., 2023)

7.2 Precision agriculture tools

Precision agriculture tools, including precision nutrient management systems, have been shown to significantly improve the productivity and efficiency of direct-seeded rice. For instance, the use of Nutrient Expert® and SPAD meter-based nitrogen management has been demonstrated to enhance grain yields and water productivity while reducing nitrogen use by approximately 27.1% (Pratap et al., 2022). These tools help in optimizing the application of fertilizers, thereby increasing nutrient use efficiency and reducing environmental impact (Sadhukhan et al., 2023).

7.3 Digital decision support systems

Digital decision support systems (DSS) are increasingly being used to optimize water and fertilizer management in rice cultivation. These systems integrate data from various sources to provide real-time recommendations for irrigation and fertilization, thus enhancing resource use efficiency. For example, DSS can help in determining the optimal timing and amount of irrigation and fertilizer application, which can lead to improved yields and reduced input costs (Santiago‐Arenas et al., 2021; Zhu et al., 2024a). By leveraging data analytics, these systems can also predict crop performance under different management scenarios, aiding in better decision-making (Zhu et al., 2024b).

8 Challenges and Future Directions

The adoption of direct seeding in rice production faces several barriers despite its potential benefits in water and labor savings. One significant challenge is the increased fertilizer use associated with direct seeding, which can deter farmers due to higher input costs and environmental concerns (Zhang and Hu, 2022). Additionally, the transition from traditional transplanting methods to direct seeding requires changes in farm management practices, which can be a barrier for farmers accustomed to conventional methods (Zhang et al., 2018). The need for precise water and nitrogen management to optimize yield and resource use efficiency further complicates adoption (Pratap et al., 2022).

Enhancing the climate resilience of direct-seeded rice systems is crucial, given the increasing variability in weather patterns. Water management strategies such as alternate wetting and drying (AWD) have shown promise in reducing water use and greenhouse gas emissions, contributing to more sustainable rice production (Islam et al., 2020). However, these methods require careful implementation to maintain yield levels, which can be challenging under unpredictable climate conditions (Santiago‐Arenas et al., 2021). The integration of organic fertilizers has also been suggested to improve soil health and resilience, although this approach requires further research to optimize its effectiveness in different environmental contexts (Guo et al., 2022).

Future research should focus on optimizing water and fertilizer management to enhance yield and resource use efficiency in direct-seeded rice systems. Studies have highlighted the potential of precision nitrogen management and controlled-release fertilizers to improve nitrogen use efficiency and reduce environmental impacts (Zhang et al., 2018; Fu et al., 2023). Additionally, exploring the synergistic effects of combined organic and inorganic fertilization on soil health and yield could provide insights into sustainable practices (Guo et al., 2022). Research should also prioritize developing climate-resilient rice varieties and management practices that can withstand extreme weather events while maintaining productivity (Zhu et al., 2024b).

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Conflict of Interest Disclosure

The author affirms 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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