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Innovations in Water Management for Rice Cultivation: Benefits of Alternating Wetting and Drying

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Abstract Rice cultivation is a major consumer of water resources, and traditional continuous flooding (CF) methods contribute significantly to water scarcity and environmental degradation. This study explores the benefits of the Alternate Wetting and Drying (AWD) irrigation technique as an innovative water management practice for rice cultivation. AWD has been shown to reduce water usage by 25-70% and greenhouse gas emissions by up to 95%, while maintaining or even improving rice yields by 1-20% compared to CF. Additionally, AWD enhances water productivity, reduces the accumulation of harmful heavy metals in rice grains, and improves grain quality. Despite these advantages, the adoption of AWD faces challenges such as the need for precise water level control, institutional support, and farmer education. This study synthesizes findings from various studies to highlight the potential of AWD to contribute to sustainable rice production, mitigate climate change impacts, and support the livelihoods of rice farmers in water-scarce regions.
Keywords Rice cultivation; Alternate Wetting and Drying; Water management; Greenhouse gas emissions; Sustainable agriculture

1 Introduction

Rice (*Oryza sativa* L.) is a staple food for more than half of the world's population, particularly in Asia, where it is a primary source of calories and nutrition. As an aquatic plant, rice has a great demand for water, and insufficient water supply under drought conditions can directly affect its growth and development (Zhu and Shen, 2024). Traditional rice cultivation methods, such as continuous flooding (CF), require substantial amounts of water, making rice one of the most water-intensive crops. This high-water demand poses significant challenges, especially in regions facing water scarcity and increasing competition for water resources due to urbanization and industrialization (Thakur et al., 2018; Sriphirom et al., 2019; He et al., 2020). The sustainability of rice production is further threatened by climate change, which exacerbates water shortages and affects the reliability of water supplies (Maneepitak et al., 2019; Morshed, 2023).

Innovative water management practices are crucial to ensure the sustainability of rice cultivation. These practices aim to reduce water usage, enhance water productivity, and mitigate the environmental impacts associated with traditional irrigation methods. Effective water management can also help maintain or even improve rice yields, ensuring food security for growing populations (Patikorn et al., 2018; Bwire et al., 2022). Among these innovations, the alternate wetting and drying (AWD) technique has gained attention for its potential to address the dual challenges of water scarcity and greenhouse gas emissions (Kwanyuen et al., 2021; Pham et al., 2021).

The AWD technique involves periodically allowing the rice field to dry out after the disappearance of ponded water before re-irrigating. This method contrasts with the continuous flooding approach, where fields are kept submerged throughout the growing season. AWD has been shown to significantly reduce water usage by up to 40% while maintaining or even increasing rice yields under certain conditions (Sriphirom et al., 2019; He et al., 2020). Additionally, AWD can lower greenhouse gas emissions, particularly methane, by reducing anaerobic conditions in the soil (Sriphirom et al., 2019; Acosta-Motos et al., 2020). The technique's effectiveness depends on precise water level control, which can be enhanced through technologies such as the Internet of Things (IoT) (Pham et al., 2021).

This study comprehensively evaluates the benefits and challenges associated with the Alternate Wetting and Drying (AWD) technique in rice cultivation. Its specific objectives encompass assessing the technique's impact on water usage and water productivity, evaluating its effects on rice yields and yield components, analyzing its environmental benefits particularly in reducing greenhouse gas emissions, and identifying the optimal conditions for AWD's effectiveness as well as the potential barriers to its widespread adoption. By synthesizing findings from multiple studies, this study endeavors to offer a holistic perspective on the potential of AWD to enhance the sustainability of rice cultivation practices.

2 Traditional Water Management Practices in Rice Cultivation

2.1 Continuous flooding method

The continuous flooding (CF) method is a traditional water management practice in rice cultivation where rice paddies are kept submerged under water throughout most of the growing season. This method ensures that the rice plants have a constant supply of water, which is crucial for their growth and development. CF is widely used because it helps control weeds, pests, and diseases, and maintains soil temperature, which is beneficial for rice growth (Ishfaq et al., 2020; Subedi and Poudel, 2021). However, this method requires a significant amount of water, making it less sustainable in regions facing water scarcity (He et al., 2020; Kwanyuen et al., 2021).

2.2 Limitations and challenges

Despite its widespread use, the continuous flooding method has several limitations and challenges. One of the primary issues is the high water requirement, which is becoming increasingly unsustainable due to global water scarcity and competition for water resources from other sectors (Kwanyuen et al., 2021; Subedi and Poudel, 2021). Additionally, CF can lead to the accumulation of heavy metals such as arsenic and mercury in rice grains, posing health risks to consumers (Ishfaq et al., 2020). The method also contributes to the decline in soil health, including reduced soil organic matter and increased micronutrient deficiencies, which threaten the long-term sustainability of rice production (Livsey et al., 2019; Ishfaq et al., 2020).

2.3 Environmental impact

The environmental impact of the continuous flooding method is significant. CF is a major contributor to greenhouse gas (GHG) emissions, particularly methane (CH_4), which is released from the anaerobic decomposition of organic matter in flooded rice paddies (Jiang et al., 2019; Sriphirom et al., 2019). Methane is a potent greenhouse gas, and its emission from rice fields contributes to global warming. Additionally, CF can lead to water pollution due to the runoff of fertilizers and pesticides, which can contaminate nearby water bodies (Gonçalves et al., 2022). The method also results in high water consumption, which can deplete local water resources and affect the availability of water for other uses (Maneepitak et al., 2019; He et al., 2020).

In summary, while the continuous flooding method has been a reliable practice for rice cultivation, its high water demand, negative impact on soil health, and significant environmental footprint highlight the need for more sustainable water management practices in rice farming.

3 Alternating Wetting and Drying (AWD): An Overview

3.1 Definition and process of AWD

Alternating Wetting and Drying (AWD) is a water management technique used in rice cultivation that involves the periodic drying and re-watering of rice fields. This method contrasts with the traditional continuous flooding (CF) system, where fields are kept submerged throughout the growing season. In AWD, the water level is allowed to drop to a certain threshold, typically 15 cm below the soil surface, before re-watering to a depth of about 5 cm (Figure 1). This cycle is repeated throughout the growing period, except during the flowering stage when a shallow water depth is maintained to ensure optimal grain filling (Mubeen and Jabran, 2019; Ishfaq et al., 2020; Enriquez et al., 2021).

Mallareddy et al. (2023) illustrates a perforated plastic field tube used in Alternate Wetting and Drying (AWD) irrigation for rice cultivation. AWD, developed by the International Rice Research Institute (IRRI), is a water-saving technique that alternates between flooding and drying phases, enhancing water-use efficiency and reducing greenhouse gas emissions. The field tube, partially submerged in the soil, allows farmers to monitor the water table and decide when to irrigate. When the water table drops 10-15 cm below the soil surface, irrigation is needed. This method optimizes water usage while preventing stress from drought, ensuring that rice yields remain stable. AWD is widely implemented in Asian countries, proving effective in conserving resources while maintaining productivity.

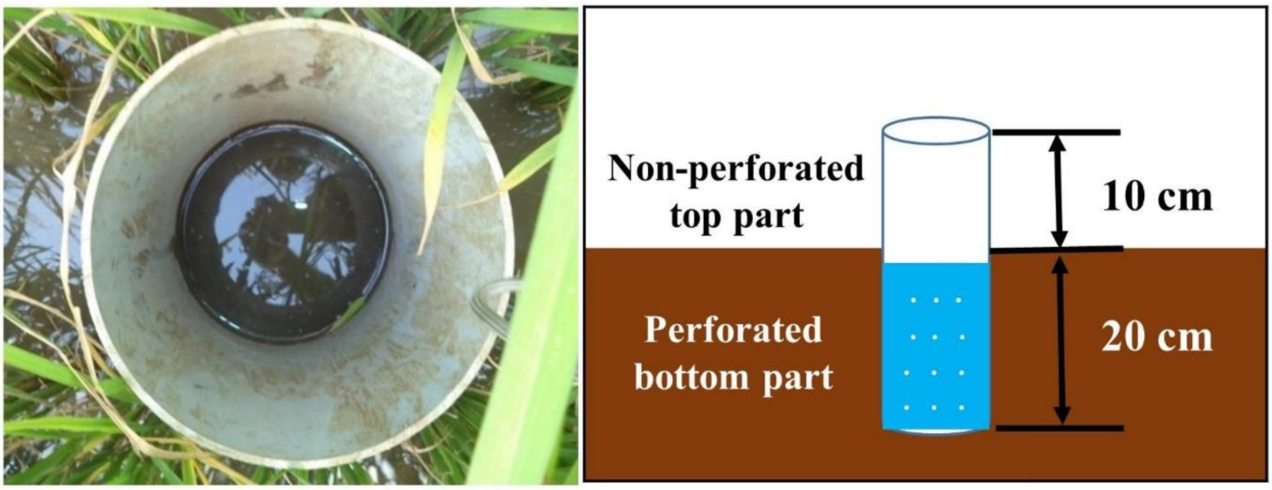

Figure 1 Perforated plastic field tube to examine the below-ground water table in AWD (Adopted from Mallareddy et al., 2023)

3.2 Historical development of AWD

The development of AWD as a water-saving technique has been driven by the need to address water scarcity and reduce the environmental impact of rice cultivation. Initially, AWD was introduced as a response to the high water demand and greenhouse gas emissions associated with CF systems. Over the past two decades, AWD has gained traction in various rice-producing regions, including the Philippines, Thailand, and Malaysia, due to its potential to conserve water and mitigate methane emissions (Sriphirom et al., 2019; Ishfaq et al., 2020; Enriquez et al., 2021). In the Philippines, for example, AWD has been scaled up through national policy adoption, supported by local adaptations and innovations (Enriquez et al., 2021).

3.3 Comparison with traditional methods

Compared to the traditional CF method, AWD offers several advantages. It significantly reduces water usage, with studies reporting water savings ranging from 25% to 70% (Mubeen and Jabran, 2019; Sriphirom et al., 2019; Ishfaq et al., 2020). Additionally, AWD has been shown to decrease methane emissions by 11% to 95%, depending on the specific implementation and environmental conditions (Sriphirom et al., 2019; Ishfaq et al., 2020; Malumpong et al., 2020). While CF systems are known for their high water consumption and associated environmental issues, AWD provides a more sustainable alternative by improving water use efficiency and reducing the accumulation of harmful substances like arsenic and mercury in rice grains (Mubeen and Jabran, 2019; Ishfaq et al., 2020; Monaco et al., 2021).

However, the effectiveness of AWD can vary based on factors such as soil type, weather conditions, and the degree of dryness allowed between wetting cycles. For instance, incomplete AWD, where the drying phase is interrupted by rainfall, may not achieve the same benefits as complete AWD, particularly in terms of yield and greenhouse gas emissions (Sriphirom et al., 2019). Despite these challenges, AWD has been successfully implemented in various regions, demonstrating its potential as a viable alternative to traditional rice cultivation methods (Mubeen and Jabran, 2019; Sriphirom et al., 2019; Ishfaq et al., 2020; Enriquez et al., 2021).

In summary, AWD represents a significant innovation in water management for rice cultivation, offering substantial benefits in terms of water conservation, environmental sustainability, and potentially improved grain quality. Its adoption and adaptation continue to evolve, driven by the need to address the challenges of water scarcity and climate change in rice-producing regions worldwide.

4 Benefits of Alternating Wetting and Drying

4.1 Water conservation and efficiency

Alternating Wetting and Drying (AWD) is a water management practice that significantly reduces water usage in rice cultivation. Studies have shown that AWD can reduce total water inputs by 25-70% compared to the conventional continuously flooded (CF) system (Ishfaq et al., 2020). In China, optimized AWD methods decreased irrigation water usage by 40% while increasing water productivity by 34% (He et al., 2020). Additionally, AWD systems have been reported to use 11.88% and 3.79% less water during the wet and dry seasons, respectively, compared to CF (Sriphirom et al., 2019). This reduction in water use is crucial for regions facing water scarcity and helps in the sustainable management of water resources.

4.2 Yield stability and crop performance

AWD not only conserves water but also maintains or even improves rice yields. For instance, mild AWD has been shown to increase rice yields by 1-6% compared to CF (He et al., 2020). Complete AWD during the dry season enhanced rice yield by 2.42% through increased tiller and panicle numbers (Sriphirom et al., 2019). Furthermore, the combination of AWD with appropriate nitrogen management (e.g., polymer-coated urea) has been found to synergistically increase grain yield and resource use efficiency (Zhang et al., 2021). These findings suggest that AWD can provide stable or improved crop performance while conserving water.

4.3 Reduction of greenhouse gas emissions

One of the significant environmental benefits of AWD is the reduction in greenhouse gas (GHG) emissions, particularly methane (CH_4). AWD can reduce CH_4 emissions by 11-95% compared to CF (Ishfaq et al., 2020). In a meta-analysis, non-continuous flooding practices, including AWD, reduced CH_4 emissions by 53% (Jiang et al., 2019). Additionally, optimized AWD methods in China reduced GHG emissions by 37% through lower methane emissions and less energy consumption from irrigation (He et al., 2020). Although AWD can increase nitrous oxide (N_2O) emissions, the overall global warming potential (GWP) is still lower than that of CF (Jiang et al., 2019; Sriphirom et al., 2019).

4.4 Soil health and nutrient management

AWD positively impacts soil health and nutrient management. It improves soil aeration, which enhances root growth and canopy structure (Mubeen and Jabran, 2019). AWD also reduces the accumulation of heavy metals such as arsenic and mercury in rice grains, thereby improving grain quality and safety (Ishfaq et al., 2020). Moreover, AWD has been shown to increase the concentration of grain micronutrients like zinc (Ishfaq et al., 2020). The practice of AWD, combined with appropriate fertilization strategies, can enhance nutrient use efficiency and reduce the environmental footprint of rice cultivation (Zhang et al., 2021).

4.5 Economic benefits for farmers

The economic viability of AWD is another critical benefit. By reducing water and energy inputs, AWD lowers the cost of irrigation, making it a more cost-effective option for farmers (He et al., 2020; Ishfaq et al., 2020). In China, the economic return from optimized AWD methods could largely offset the risk of yield losses (He et al., 2020). Additionally, AWD can increase farmers' income by maintaining or improving yields while reducing input costs (He et al., 2020). The adoption of AWD can thus provide significant economic benefits, contributing to the overall sustainability and profitability of rice farming.

In summary, AWD offers multiple benefits, including water conservation, yield stability, reduction in GHG emissions, improved soil health, and economic advantages for farmers. These benefits make AWD a promising alternative to conventional rice cultivation practices, particularly in regions facing water scarcity and environmental challenges.

5 Challenges and Limitations of AWD

5.1 Adoption barriers

Adoption of the Alternate Wetting and Drying (AWD) technique faces several barriers. One significant barrier is the lack of institutional support and the complexity of agricultural and socioeconomic systems, which can hinder widespread adoption despite the technique's benefits (Ishfaq et al., 2020). Additionally, the high fixed costs associated with AWD can deter farmers, particularly small-scale ones, from adopting this water-saving technology (Suwanmaneepong et al., 2023). In the Philippines, the dominant focus on technology transfer without considering local contextual factors has also limited the impact of AWD (Enriquez et al., 2021). Furthermore, the perception of AWD as a risky practice, especially in terms of crop failure, remains a significant barrier to its adoption (Suwanmaneepong et al., 2023).

5.2 Technical and logistical challenges

Implementing AWD effectively requires precise control over water levels, which can be technically challenging. Incomplete AWD, where water levels are not managed correctly, can lead to increased emissions of nitrous oxide (N_2O) and reduced rice yields (Sriphirom et al., 2019). The variability in soil conditions, irrigation timing, and environmental factors can also affect the success of AWD, making it less predictable and harder to manage compared to continuous flooding (CF) (Subedi and Poudel, 2021). Additionally, the need for regular monitoring and adjustments to water levels can be labor-intensive and require technical knowledge that some farmers may lack (Samoy-Pascual et al., 2021).

5.3 Regional variations and climatic factors

The effectiveness of AWD can vary significantly based on regional and climatic conditions. For instance, in regions with frequent rainfall, such as during the wet season in Thailand, incomplete AWD can occur, leading to suboptimal results (Sriphirom et al., 2019). In contrast, during the dry season, complete AWD has been shown to be more effective in reducing greenhouse gas emissions and saving water (Sriphirom et al., 2019). The hydrological impact of AWD also varies, with some regions experiencing enhanced streamflow and increased water availability, while others may face challenges due to reduced precipitation and water stress (Schneider et al., 2019). These regional and climatic variations necessitate tailored approaches to AWD implementation to ensure its effectiveness.

5.4 Socio-economic constraints

Socio-economic factors play a crucial role in the adoption and success of AWD. Farmers' understanding of the safe and proper application of AWD, along with the availability of crop insurance to mitigate risks, is essential for encouraging adoption (Suwanmaneepong et al., 2023). Economic viability is another critical factor; while AWD can be economically beneficial, the initial costs and the need for technical and financial support can be prohibitive for some farmers (Gharsallah et al., 2023). In regions like northern Italy, farmers have expressed willingness to adopt AWD but require substantial support to do so (Gharsallah et al., 2023). Additionally, the social dynamics within farming communities, such as the influence of irrigators' associations and enforced rotational irrigation schedules, can significantly impact the adoption of AWD (Samoy-Pascual et al., 2021).

By addressing these challenges and limitations, AWD can be more effectively scaled and implemented, contributing to sustainable rice cultivation and water management.

6 Case Study

6.1 Overview of the selected region/field

The selected region for this case study is the Mekong Delta in Vietnam, a critical area for rice production that faces significant challenges due to reduced rainfall and water stress. The livelihoods of millions of rice farmers in this region are increasingly vulnerable, necessitating the adoption of water-saving practices to sustain rice production and enhance resilience to climatic changes (Figure 2) (Pham et al., 2021). Additionally, the Center of Portugal was also considered, where traditional continuous flooding methods have been predominant, leading to high water demand and environmental issues such as pollution and methane emissions (Gonçalves et al., 2022).

Pham et al. (2021) illustrates a pilot study conducted from September 2017 to August 2019 in Vietnam's Mekong Delta, covering Can Tho, Tra Vinh, and An Giang provinces. This pilot involved 82 farmers and one farm enterprise, exploring the implementation of IoT-based Alternate Wetting and Drying (AWD) techniques across diverse environmental conditions. The three distinct locations provided a broad perspective on the benefits and challenges of introducing advanced water management practices in varied agricultural settings. The study's regional diversity allowed for a comprehensive assessment of AWD's effectiveness in reducing water usage and enhancing crop yields, while also addressing the specific needs and constraints of different farming environments. The map highlights the geographical spread and structural differences of the test sites.

Figure 2 Map of the project locations (Adopted from Pham et al., 2021)

6.2 Implementation of AWD in the region

In the Mekong Delta, the implementation of Alternate Wetting and Drying (AWD) was facilitated by the use of Internet of Things (IoT) technology to provide precise water level measurements. This technology allowed farmers to maximize the benefits of AWD by ensuring accurate irrigation scheduling, which led to significant water savings and reduced irrigation energy costs (Pham et al., 2021). In the Center of Portugal, AWD was implemented using field irrigation evaluation methods, which demonstrated the potential to save about 10% of irrigation water while maintaining crop productivity (Gonçalves et al., 2022).

6.3 Impact assessment: water use, yield, and environmental benefits

The implementation of AWD in the Mekong Delta resulted in 13-20% water savings over manual AWD methods, reduced irrigation energy costs by 25%, and moderately enhanced rice yields by 2-11% (Pham et al., 2021). In Portugal, AWD allowed for an additional 10 to 29 days of dry soil, contributing to water savings and a reduced yield impact. The use of water level sensors was crucial in managing soil water deficits and mild crop stress during dry periods (Gonçalves et al., 2022). Furthermore, studies in China and other regions have shown that AWD can reduce irrigation water usage by 40%, increase water productivity by 34%, and reduce greenhouse gas emissions by 37% (He et al., 2020). Similarly, AWD has been found to reduce total water inputs by 25-70%, methane emissions by 11-95%, and heavy metal accumulation in rice grains, while maintaining or improving paddy yield (Ishfaq et al., 2020).

6.4 Lessons learned and Future recommendations

The case studies highlight the importance of precise water management and the integration of technology to optimize AWD implementation. The use of IoT technology in the Mekong Delta demonstrated that accurate water level measurements are essential for maximizing the benefits of AWD, suggesting that future efforts should focus on promoting the adoption of such technologies among smallholder farmers (Pham et al., 2021). In Portugal, the success of AWD in saving water and maintaining yields underscores the need for guidelines to promote on-farm scale AWD automation and the development of smart irrigation supplies (Gonçalves et al., 2022). Additionally, the findings from China and other regions emphasize the need for policies that support and invest in both water management and high-yielding cultivation practices to achieve sustainable rice production (He et al., 2020; Ishfaq et al., 2020). Future research should continue to explore the long-term impacts of AWD on soil health, nutrient dynamics, and overall ecosystem sustainability to further refine and optimize this irrigation practice.

7 Comparative Analysis of AWD with Other Water-Saving Techniques

7.1 System of rice intensification (SRI)

The System of Rice Intensification (SRI) is a method that aims to increase the yield of rice produced in farming. SRI involves changes in the management of plants, soil, water, and nutrients. It is labor-intensive and requires precise timing and management, which can be a barrier for adoption in labor-scarce regions. However, it has been shown to improve water use efficiency and yield in some cases. SRI can be less feasible for poor farmers due to the high labor requirements and the need for specialized knowledge and training (Mallareddy et al., 2023).

7.2 Direct seeding of rice (DSR)

Direct Seeding of Rice (DSR) is another water-saving technique that involves sowing seeds directly into the field rather than transplanting seedlings. This method can save water and labor, making it suitable for areas with labor shortages. DSR can reduce the duration to maturity and lower production costs. However, it faces challenges such as weed infestation, which can significantly reduce yields if not managed properly. Effective weed management strategies are crucial for the success of DSR (Shekhawat et al., 2020; Pratap et al., 2022; Mallareddy et al., 2023).

7.3 Dry-seeded rice and other techniques

Dry-Seeded Rice (dry-DSR) is a variant of DSR where seeds are sown in dry soil. This method is resource-efficient and environmentally friendly, but it faces issues with seedling emergence and growth. Seed treatments with substances like wood vinegar and biochar have been shown to improve germination and seedling growth, enhancing the overall yield of dry-DSR (Zhang et al., 2022). Other techniques such as aerobic rice and drip-irrigated rice also aim to save water but are often not feasible for small-scale farmers due to high costs and labor requirements (Mallareddy et al., 2023).

7.4 Comparative benefits and drawbacks

Alternate Wetting and Drying (AWD) stands out as a promising water-saving technique due to its balance of cost-effectiveness, water savings, and environmental benefits. AWD can reduce water inputs by 25-70%, lower methane emissions by 11-95%, and decrease the accumulation of heavy metals in rice grains while maintaining or even improving yields (Sriphirom et al., 2019; Ishfaq et al., 2020; Enriquez et al., 2021). However, the adoption of AWD can be hindered by the need for precise water management and the risks associated with crop failure, especially in areas with unpredictable rainfall (Samoy-Pascual et al., 2021; Suwanmaneepong et al., 2023).

In comparison, SRI and DSR offer significant water savings and yield improvements but come with higher labor and management requirements. Dry-DSR, while efficient, requires additional interventions like seed treatments to overcome initial growth challenges. Each method has its own set of advantages and limitations, and the choice of technique often depends on local conditions such as labor availability, soil type, and climate (Shekhawat et al., 2020; Pratap et al., 2022; Zhang et al., 2022; Mallareddy et al., 2023).

In summary, while AWD offers a balanced approach with significant water and environmental benefits, the choice between AWD, SRI, DSR, and other techniques should be made based on specific local conditions and resource availability.

8 Future Directions in Water Management for Rice Cultivation

8.1 Innovations in AWD techniques

Alternate Wetting and Drying (AWD) has shown significant promise in reducing water usage and greenhouse gas emissions while maintaining or even improving rice yields. Future innovations in AWD techniques could focus on optimizing the timing and degree of soil drying to maximize benefits. For instance, studies have shown that complete AWD can reduce methane emissions by up to 49% and water use by 42% compared to continuous flooding (CF) (Chidthaisong et al., 2018). However, incomplete AWD can lead to increased nitrous oxide emissions and reduced yields, highlighting the need for precise water level control (Patikorn et al., 2018; Sriphirom et al., 2019). Further research could explore automated water management systems that use sensors and IoT technology to maintain optimal water levels, thereby reducing the risk of incomplete AWD and enhancing overall efficiency (Patikorn et al., 2018; Sriphirom et al., 2019).

8.2 Integration with precision agriculture

Integrating AWD with precision agriculture technologies offers a promising avenue for enhancing water management in rice cultivation. Precision agriculture tools, such as remote sensing, GPS, and data analytics, can provide real-time information on soil moisture, crop health, and weather conditions, enabling more precise and efficient water management. For example, the use of sensors to monitor soil moisture levels can help farmers implement AWD more effectively, ensuring that water is applied only when necessary (Ishfaq et al., 2020; Enriquez et al., 2021). Additionally, precision agriculture can aid in the optimal application of fertilizers and other inputs, further improving the sustainability and productivity of rice farming (Mubeen and Jabran, 2019; Sriphirom et al., 2020).

8.3 Policy support and farmer training

The successful adoption of AWD and other innovative water management practices requires robust policy support and comprehensive farmer training programs. Policies that incentivize water-saving practices and provide financial support for the adoption of new technologies can significantly enhance the uptake of AWD (Alauddin et al., 2020; Suwanmaneepong et al., 2023). Training programs that educate farmers on the benefits and proper implementation of AWD are equally crucial. For instance, studies have shown that farmers' understanding of AWD and its advantages is positively associated with higher adoption rates (Suwanmaneepong et al., 2023). Additionally, providing crop insurance and other risk mitigation measures can help alleviate farmers' concerns about potential yield losses, further encouraging the adoption of AWD (Alauddin et al., 2020; Suwanmaneepong et al., 2023).

8.4 Research gaps and opportunities

Despite the proven benefits of AWD, several research gaps and opportunities remain. One key area is the need for more localized studies to understand the specific conditions under which AWD is most effective. For example, the impact of AWD on greenhouse gas emissions and water use can vary significantly depending on soil type, weather conditions, and other local factors (Chidthaisong et al., 2018; Morshed et al., 2023). Another important research area is the long-term effects of AWD on soil health and crop productivity. While short-term studies have shown positive results, more research is needed to understand the long-term sustainability of AWD (Ishfaq et al., 2020; Enriquez et al., 2021). Additionally, exploring the combination of AWD with other sustainable practices, such as biochar application, could offer further benefits in terms of reducing emissions and improving soil health (Sriphirom et al., 2020). Addressing these research gaps will be crucial for optimizing AWD and ensuring its widespread adoption in rice cultivation.

By focusing on these future directions, we can enhance the sustainability and resilience of rice farming, ensuring food security in the face of growing water scarcity and climate change challenges.

9 Concluding Remarks

The implementation of Alternate Wetting and Drying (AWD) in rice cultivation has shown significant potential in reducing water usage and greenhouse gas (GHG) emissions while maintaining or even enhancing rice yields. Studies have demonstrated that AWD can reduce water inputs by 25-70% and methane emissions by 11-95% compared to the conventional continuous flooding (CF) method. Additionally, AWD has been found to improve water use efficiency and nutrient dynamics, leading to better grain quality and increased economic viability. However, the effectiveness of AWD can vary depending on factors such as soil type, weather conditions, and the degree of dryness.

The adoption of AWD presents a promising pathway for sustainable rice cultivation. By significantly reducing water usage, AWD addresses the critical issue of water scarcity, which is increasingly threatening global rice production. Moreover, the reduction in GHG emissions associated with AWD contributes to mitigating climate change impacts, aligning with global sustainability goals. The improved water use efficiency and nutrient uptake under AWD also enhance the overall productivity and economic returns for farmers, making it a viable alternative to CF. However, successful implementation requires careful management and monitoring to avoid incomplete AWD, which can lead to increased emissions and yield reductions.

AWD has emerged as a critical innovation in water management for rice cultivation, offering a sustainable solution to the challenges of water scarcity and climate change. Its ability to reduce water usage and GHG emissions while maintaining or enhancing yields makes it a valuable tool for ensuring the long-term sustainability of rice production. However, widespread adoption of AWD requires addressing several challenges, including the need for precise water level monitoring, farmer education, and institutional support. As global water resources continue to dwindle, the role of AWD in global rice production will become increasingly important, necessitating concerted efforts to scale its adoption and optimize its implementation for diverse agricultural contexts.

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Conflict of Interest Disclosure

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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