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A review on technological innovations on alternate wetting and drying: Its impact on water-saving, economic, environmental, and social aspects

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Abstract

This review emphasizes the crucial requirement for water-saving methods in rice cultivation because of worldwide water scarcity. Alternate wetting and drying (AWD) irrigation, proposes a viable solution, which could cut water usage by as much as 38% without negatively affecting rice production, and might even boost it. Implementing AWD can result in financial savings for farmers, reductions in greenhouse gases, and enhanced rice quality characterized by lower arsenic and mercury levels. Nevertheless, the study points out that the broad implementation of AWD faces obstacles, such as the necessity for better monitoring and management systems. To address it, this review centers on technological progress in AWD, particularly advancements made between 2015 and 2024. This study reviewed and examined peer-reviewed articles, conference proceedings, and technical reports from pertinent databases through the use of specific search terms. The review consolidates current researches on technological developments, assessing their influence on crop yield, water usage, fertilizer application, and overall sustainability. The research highlights the ability of IoT-powered automated irrigation systems to amplify the advantages of Alternate Wetting and Drying (AWD). Results show that automated AWD, enabled by the Internet of Things, can lead to a significant decrease in water usage (as much as 36%), lesser irrigation expenses, and higher crop productivity when compared with conventional methods. Equipped with features like sensors, cloud computing, and intuitive interfaces, the systems offer farmers with instant data and remote operation capabilities for efficient water usage. The study recognizes the ecological advantages related with AWD, particularly in decreasing methane emissions, however, attentions about the possibility of heightened nitrous oxide emissions is necessary. This study encourages for more research to overcome problems in the application and to expand the use of these technologies for broader acceptance, recognizing that automated AWD can play a role in helping sustainable rice cultivation.

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Introduction

In crop production, water shortage has been a pressing problem worldwide. Specifically in rice farming, water management related challenges influence adversely food production, economy, and water security. To mitigate this adverse effect of this situation, researchers conducted and promoted efficient water use, cost-saving technologies, and water conservation practices while maintaining the yield of rice (Mallareddy *et al.*, 2023; Suwanmaneepong *et al.*, 2023). Alternative wetting and drying (AWD) irrigation techniques have been studied as methods to reduce the amount of water utilized in rice farming, consequently increase water-use efficiency and sustainability (Arouna *et al.*, 2023; Alauddin *et al.*, 2020; Djaman *et al.*, 2018; FAO, (n.d.); IRRI, (n.d.)). The Alternate Wetting and Drying (AWD) is a rice irrigation method introduced by the International Rice Research Institute (IRRI) and adopted by many rice-producing countries. Accordingly, the AWD technology maintains soil moisture ranging between 0-40 kPa through controlled irrigation by cyclic flooding and drying of rice fields thus needing the monitoring of water depth by means of field water tubes. To ensure safe AWD technology implementation, rice fields are flooded to a depth that ranges from 5cm after drying to 10cm below the soil and pause for about 2-3 weeks to control weeds with flooded water.

Results of various studies indicate that Alternate Wetting and Drying (AWD) irrigation technology has shown good results, such as decreasing the amount of water in rice farming while maintaining its yield potential, making the technology feasible, particularly in areas where water for irrigation is a limiting factor for rice to reach its potential yield (Sriphirom *et al.*, 2019; Ishfaq *et al.*, 2020; IRRI (n.d.)). Further, other studies show that adapting the AWD technology could potentially decrease greenhouse gas emissions (Morshed, 2024; Kraus *et al.*, 2022; Ishfaq *et al.*, 2020) qualifying the AWD technology is an environment-friendly and water-saving technology in rice production. This makes the technology became popular and widely adapted method as a water-saving technology in rice production (Samoy-Pascual *et al.*, 2021; Alauddin *et al.*, 2020; Setyanto *et al.*, 2017; Sibayan *et al.*, 2017; Valdivia *et al.*, 2016; Nalley *et al.*, 2015; Lampayan *et al.*, 2014).

Economic effects of AWD technology on rice farming were also evaluated by various studies and showed that the AWD technology posed a positive impact on irrigation practices.

According to Ishfaq *et al.* (2020), adapting the AWD technology lessens significantly the volume of water use by up to 30% and 38% (Suwanmaneepong *et al.*, 2023; Lampayan *et al.*, 2015) while ensuring optimum crop growth and yield. This significant decrease in water-use could save farmers' money and resources on irrigation and pumping costs (Ole Sander, 2014), thus, reducing the production cost per kilogram of rice. The method do not only decrease the volume of water needed for irrigation but also helps in preserving soil health and fertility by allowing periods of aeration between wetting cycles. AWD's effectiveness in saving water emphasizes its potential as a sustainable irrigation method, providing advantages for both farmers and the environment.

Accordingly, the AWD's effectiveness as a water-saving technology for rice without affecting its growth and yield potential depends on close monitoring of the farmers. Hence, to effectively implement the technology and to realize its potential impact on water saving, economic, environmental, and social aspects, close monitoring is required. However, at the farmers' level, close monitoring during the adaption and implementation of the technology would require additional jobs for the farmers.

The potential drawback in adapting and implementing AWD technology at the farmers' level could be addressed through integration of technological innovations on AWD. This paper aims to examine and synthesize technological innovations in Alternate Wetting and Drying (AWD) irrigation methods from 2015 to 2024, with a particular focus on enhancing water use efficiency and cost-effectiveness in agricultural practices. It explores advancements in tools, techniques, and systems that support the implementation of AWD, evaluates their impacts on water savings, crop productivity, and economic viability, and identifies the challenges and opportunities for scaling these technologies in diverse agricultural contexts.

Research methods and approach

This review adopts a systematic and integrative approach to analyze technological innovations in Alternate Wetting and Drying (AWD) irrigation methods. The adopted methodology was based on the identification and in-depth analysis of original research articles published from 2014-2024, all subject areas, and related technical notes. Relevant peer-reviewed open-access journal articles, conference proceedings, and technical reports were identified from reputable database such as Scopus. The following Boolean searches were used: Alternate Wetting and Drying Irrigation (1,338); alternate wetting and drying irrigation, rice, yield (1,050); alternate wetting and drying irrigation, rice, yield, water-use (1,040); alternate wetting and drying irrigation, rice, yield, water-use, CH_4, N_2O, GHG (52); alternate wetting and drying irrigation, rice, yield, water-use, Fertilizer/nutrient (566); alternate wetting and drying, internet of things (69).

This study comprised a broad literature review to summarize, evaluate, and integrate the previous research on the main aspects associated with technological innovations applied to alternate wetting and drying, including their influence on crop yield, water use, and fertilizer, as well as their effect on economic, environmental, and social sustainability.

Effect of alternate wetting and drying on water use, yield, and fertilizers

Alternate wetting and drying (AWD) have emerged as a promising water-saving irrigation technique for sustainable rice production, offering numerous benefits across various aspects of cultivation. Compared to conventional continuous flooding (CF), AWD demonstrably conserves water, with studies reporting reductions in water consumption ranging from 19% to 70% (Loaiza *et al.*, 2024; Atwill *et al.*, 2023; Neogi *et al.*, 2018; Ishfaq *et al.*, 2020; Sha *et al.*, 2022). This translates to lower irrigation costs for farmers (Neogi *et al.*, 2018) and reduced energy consumption associated with pumping water. Nalley *et al.* (2015) further reported water use efficiency (WUE) increases of 21% to 56% under AWD compared to CF.

This water-saving potential can be further enhanced by incorporating rice straw/stubble during dry fallow tillage (Samoy-Pascual *et al.*, 2019). Sriphirom *et al.* (2019) specifically found that both incomplete and complete AWD reduced water use compared to CF, with incomplete AWD (likely due to longer drying periods from rainfall interference) showing more pronounced reductions (11.88% less total water and 16.72% less irrigation water) than complete AWD (3.79% and 4.52%, respectively). Importantly, AWD can maintain rice yields comparable to CF (Loaiza *et al.*, 2024; Howell *et al.*, 2015), and in some cases, even increase them (Pramono *et al.*, 2024; Hoang *et al.*, 2023; Xu *et al.*, 2019; Ishfaq *et al.*, 2020; Sha *et al.*, 2022). Ishfaq *et al.* (2020) reported yield increases of 10-20% under AWD. Sriphirom *et al.* (2019) confirmed this potential for yield improvement with complete AWD, observing a 2.42% yield increase due to more tillers and panicles. This aligns with the yield increases observed in other studies using modified N fertilizers (Li *et al.*, 2018) and biochar application (Liu *et al.*, 2024) in conjunction with AWD. However, incomplete AWD would result to reduced yield by 9.12% (Sriphirom *et al.*, 2019). This emphasizes that although extended drying periods can maximize water savings, as noted in their incomplete AWD treatment, not properly managed AWD with prolonged drying periods which could be due to uncontrolled rainfall can negatively influence yields. Results of studies highlight the significance of correctly implemented water management in AWD application and was not directly addressed in studies focusing on more controlled AWD systems. Moreover, aside from water conserving and improving yields, Alternate Wetting and Drying (AWD) technology also offers other advantages to include reduction in the accumulation of arsenic (As) and mercury (Hg) in rice grains (Ishfaq *et al.*, 2020). Furthermore, mild AWD has been related to a better-quality grain, along with reduced kernel chalkiness, increased head rice recovery, and improved grain micronutrient concentrations (Ishfaq *et al.*, 2020). Nevertheless, AWD may also influence other grain quality qualities like chalkiness and milling recovery (Xu *et al.*, 2019; Monaco *et al.*, 2021), these effects are variety-specific and dependent on a specific AWD implementation (Xu *et al.*, 2019; Monaco *et al.*, 2021). Despite of the numerous advantages of the AWD technology which includes water savings and potential yield increases, widespread adoption of it remains limited because of complex agricultural, socio-economic factors and insufficient institutional support (Ishfaq *et al.*, 2020).

Several research studies have revealed methods for improving rice production and sustainability through the use of several soil amendments and fertilizers and irrigation practices like AWD. Ku *et al.* (2020) studied the effects of using calcium silicate ($CaSiO_3$) fertilizer under an Alternate Wetting and Drying (AWD) irrigation system. Results revealed that the use of $CaSiO_3$ with moderate application rate increased rice straw biomass and improved nitrogen (N) use efficiency, while emissions of nitrous oxide (N_2O) is reduced. But then it was observed that no significant difference in grain yield due to a lower harvest index, which shows a limited biomass conversion into grain. In contrary, Li *et al.* (2018) showed the combined effects of modified nitrogen fertilizers and shallow water depth with AWD (SWD).

The modified fertilizers like the polymer-coated controlled-release urea (CRU) and nitrapyrin-urea plus hydroquinone (NU + HQ) significantly increased grain yield by 6-35%.

Similarly, Liu *et al.* (2024) revealed the combined effects of biochar incorporation and AWD irrigation (IAWD). Results show that this combination resulted to an enhanced rice grain yield by 5-11%, and when combined with IAWD, attained the highest soil carbon sequestration (SOCS), which means a carbon-negative potential. These studies determine the potential of combining AWD with soil amendments or modified fertilizers to increase yield, a benefit not observed with the application of $CaSiO_3$ alone. In terms of enhancement of productivity, Sha *et al.* (2022) showed that zeolite application, at both 5 and 10 t ha^{-1} additions could improve grain yield ranging from 11%-21%, a water productivity ranging from 13%-20% and NEEP ranging from 13%-24% compared to non-zeolite treatments. Their research acknowledges the optimal combination for balancing decreased GHG emissions and improved yield as AWD irrigation combined with 5 t ha^{-1} of zeolite. These results offer a promising eco-economic method for sustainable rice cultivation. LaHue *et al.* (2016) further presented that AWD could reduce emissions of methane (CH_4) which ranges from 60–87% while maintaining or slightly increasing grain yields compared to conventional continuously flooded (CF) methods. The yield stability could be attributed to optimized nitrogen management under AWD, allowing similar or reduced nitrogen input requirements while supporting comparable productivity levels. This result is similar with the findings of Li *et al.* (2018) and Liu *et al.* (2024), which reported yield enhancements in rice production grown under a specific management practice combined with AWD technology. As highlighted by LaHue *et al.* (2016), the enhanced nitrogen-use efficiency under AWD could be attributed to improved root development and microbial activity, thus, enhancing nutrient availability for crop uptake. Moreover, LaHue *et al.* (2016) also found that AWD reduced total arsenic (As) concentrations in rice grains by 59–65%, resulting in improved grain quality and food safety.

Along with this finding is the significant decrease in GHG emissions by 59–88% during growing season. This result strengthens the potential of AWD to balance yield performance with climate mitigation and food safety. Nevertheless, LaHue *et al.* (2016) reminded that yield outcomes under AWD could vary due to site-specific conditions such as soil type, degree of dryness, and crop growth stages, with extended drought that could potentially lead to yield decrease because of moisture stress. This emphasizes the importance of properly implementing AWD management to optimize both yield and environmental benefits, a point further highlighted by studies that showed negative impacts on the crop yield because of poorly managed AWD.

Even though Alternate wetting and drying technology is a promising irrigation technology that offers significant potential to improve the sustainability of rice cultivation through water saving, reduction of greenhouse gases emissions, and better grain quality, research gaps remain that limit its extensive implementation. Discrepancy in yield responses under different AWD regimes is one of the important research gaps identified. While mild AWD has been revealed to maintain or even increase rice yields, severe drying periods, such as those observed in incomplete AWD systems (Sriphirom *et al.*, 2019), could affect negatively the rice yield due to moisture stress. This recommends a need for further study focusing on the optimum degree of soil drying and rewetting cycles to determine yield performance and water savings effectively. Moreover, when AWD is combined with different soil amendments (e.g., $CaSiO_3$, biochar, and modified fertilizers) shows different effective outcome with some treatments enhances the yield while others, like as $CaSiO_3$ primarily improves biomass and nitrogen use efficiency without any significant yield gains (Ku *et al.*, 2020; Liu *et al.*, 2024).

To explain these differences, research studies should consider exploring the interactions between AWD, soil amendments, and nutrient dynamics. Furthermore, site specific factors such as soil type, rainfall patterns, and varietal differences remain underexplored despite their serious influence on both yield outcomes and GHG mitigation potential, thus, should be the subject of research inquiry. Lastly, the adoption of AWD is affected by socioeconomic barriers and institutional support issues, indicating a need for policy-driven studies and AWD implementation strategies to ensure both productivity gains and climate resilience in rice production systems.

Economic, environmental, and social sustainability of alternate wetting and drying irrigation for rice

Alternate wetting and drying (AWD) irrigation technology offers numerous advantages across various aspects of rice cultivation, including environmental impacts mitigation, water usage optimization, and potentially improving economic outcomes. The main environmental benefit of adopting the AWD irrigation technology in rice production is the reduction of greenhouse gas (GHG) emissions, particularly methane (CH_4), a potent contributor to global warming. Various researches have shown significant reductions of CH_4 under AWD compared to the CF practices, with results of studies recording reductions of between 34% and 97% (LaHue *et al.*, 2016; Sander *et al.*, 2020; Ishfaq *et al.*, 2020; Hoang *et al.*, 2023; Liao *et al.*, 2020; Lagomarsino *et al.*, 2016; Sha *et al.*, 2022). This reduction could be due to the increased soil aeration during the drying periods, which prevents the activity of methanogenic microorganisms. However, a critical trade-off exists, that is, the increase in nitrous oxide emission rate during soil drying and that following soil wetting is reliant on the nitrification and denitrification cycles that are stimulated by AWD. Accordingly, the nitrogen transport taken in from the hydrolites is more efficient under AWD when compared to CF with an associated increase of denitrification by 46% and 34% reduction in CH_4 (Lagomarsino *et al.*, 2016; Hoang *et al.*, 2023; Liao *et al.*, 2020; Lagomarsino *et al.*, 2016; Sha *et al.*, 2022). An example of such an observation is the one made by Hoang *et al.* (2023) which quantifies the trade-off in this scenario and determines that with a denitrification 46% in CH_4 and a 34% reduction in N_2O and in this way a 33% decrease in the combined effect of global warming from non-AWD systems has been quantified. Despite the N_2O increase, the general impact on GWP generally remains favorable, as decrease in CH_4 often outweigh the increase in N_2O.

Additional research has studied the modifications of AWD to manage the said trade-off. According to Liu *et al.* (2024) the use of biochar incorporated with AWD further leads to a significant reduction of CH_4 that ranges from 22-38% and mitigated the increase in N_2O by at least 31%. Similarly, the study of Li *et al.* (2018) showed that modified nitrogen fertilizers could reduce N_2O emissions by 12-44% under AWD. Ku *et al.* (2020) studied the use of calcium silicate ($CaSiO_3$) under AWD, and the results show a complex relationship where $CaSiO_3$ reduced N_2O but increased CH_4 due to enhanced methanogenic activity, stressing the complex changes in microbial activity caused by AWD. Further, results of the study conducted by Sha *et al.* (2022) showed that the AWD with Zeolite application further influenced GHG emissions, with a 5 t ha^{-1} addition mitigating CH_4 emissions by 36% on the average but having no significant effect on N_2O emissions. More than GHG mitigation, AWD technology offers other environmental benefits, such as reduced grain arsenic (As) concentrations, contributing to improved food safety (LaHue *et al.*, 2016; Linquist *et al.*, 2014).

In terms of economic aspect, the AWD technology offers significant returns to rice farmers through substantial water conservation. Several studies have reported reductions in water consumption which range from 19% to 70% (Loaiza *et al.*, 2024; Atwill *et al.*, 2023; Neogi *et al.*, 2018; Ishfaq *et al.*, 2020; Sha *et al.*, 2022). This significant reduction on wtare consumption leads to a direct cost savings on irrigation expenses and net ecosystem economic profit (NEEP) by 12%-14% (Sha *et al.*, 2022). Moreover, by reducing the need for pumping and water distribution, AWD can lower energy consumption and labor costs. This enhanced water-use efficiency translates to greater profitability and contributes to the economic sustainability of rice farming. These results are of most relevant in water-scarce regions or where irrigation costs are a significant portion of production expenses of farmers (Neogi *et al.*, 2018). Nalley *et al.* (2015) further demonstrated the economic viability of adopting AWD technology, even without considering financial incentives for GHG reduction or water conservation.

The potential of this water-saving technology can be further enhanced by incorporating rice straw/stubble during dry fallow tillage (Samoy-Pascual *et al.*, 2019). Importantly, AWD can maintain rice yields which is comparable to continuous flooding (Loaiza *et al.*, 2024; Howell *et al.*, 2015) and, in some cases, even higher yield (Pramono *et al.*, 2024; Hoang *et al.*, 2023; Xu *et al.*, 2019; Ishfaq *et al.*, 2020). Specific modifications to AWD, such as Water Management with Drainage (WMD), including complete and incomplete AWD have shown to increase grain yield significantly (Li *et al.*, 2023). However, Sriphirom *et al.* (2019) emphasized the importance of proper AWD management, showing that while "complete" AWD increased yield, "incomplete" AWD (due to uncontrolled factors like rainfall) could reduce yield. This highlights the need for a careful implementation of water management in AWD. Beyond yield, Ishfaq *et al.* (2020) noted that mild AWD could improve grain quality, reducing kernel chalkiness and increasing head rice recovery. While AWD may also affect other grain quality attributes like chalkiness and milling yield (Xu *et al.*, 2019; Monaco *et al.*, 2021), however it should be noted further that these effects are variety-specific and dependent on the particular AWD implementation.

Several factors influence AWD's effectiveness and adoption have been noted by various studies. The effectiveness of AWD in mitigating GHG emissions can be influenced by factors such as the timing of rice straw incorporation (Samoy-Pascual *et al.*, 2019) and flooding duration (Lagomarsino *et al.*, 2016). Farmer adoption faces challenges, including knowledge gaps, insufficient training (Mahadi *et al.*, 2018), and mismatches between existing irrigation schemes and AWD requirements (Mahadi *et al.*, 2018). While AWD offers significant environmental and economic benefits for rice cultivation, more research is desired to improve AWD techniques for diverse field conditions, addressing the knowledge and infrastructural barriers to adoption, and fully understand the long-term impacts of AWD on soil health and ecosystem services.

Despite researches indicating the benefits of adapting the AWD technology, several key research gaps remain. While the trade-off between CH_4 and N_2O emissions is acknowledged, additional study is desired to develop precise, context-specific mitigation strategies for N_2O increases under varying AWD regimes, soil types, and climatic conditions. The long-term impacts of repeated AWD cycles on soil health, including soil organic carbon dynamics, microbial community structure and function, and nutrient cycling, require further research. Furthermore, while economic viability has been shown in some situations, more comprehensive economic analyses are needed that incorporate the full range of potential costs and benefits associated with AWD adoption across diverse farming systems and socioeconomic frameworks. Lastly, for wider and more effective adoption of AWD, researches that focus on effective dissemination and training strategies for farmers that adopts to their farming conditions and practices, is vital.

Technological innovations on alternate wetting and drying (awd) irrigation technology

The continuously growing population worldwide and changing climate conditions intensify the pressing need for progressive agricultural practices that emphasizes the urgent need for advanced farming techniques that boost yields while conserving water. Water management in irrigated rice production is critical for optimizing yields. Alternate Wetting and Drying (AWD) is an effective irrigation technique for rice but is often limited by manual implementation. Due to several drawbacks of the traditional approach of AWD especially its implementation, integrating technological innovations through automation systems could help improve its field implementation. The automation system integrates wireless sensor networks (WSNs) for monitoring water levels, irrigation systems, and environmental conditions. It relies on an IoT system issuing commands based on data from the WSNs, ensuring efficient water distribution and reduced manual intervention. The system's scalability and adaptability to different irrigation areas underscore its practicality. Despite challenges, such as social and economic factors, the paper illustrates that widespread adoption of AWD is feasible with existing sensor networks and IoT technologies. The automated system enables continuous monitoring, real-time decision-making, and equitable water distribution among farmers, potentially benefiting rice-growing nations. Future enhancements may involve data-driven approaches like machine learning and big data analysis, incorporating farmer input to optimize plant growth and yield development. Pham *et al.* (2021) showed that research on climate-smart agriculture. They show how combining IoT with conventional farming methods is practical and beneficial.

Various researches have been carried out on innovating the AWD by integrating Internet of Things (IoT) and automated irrigation system designed for precision agriculture with key objective of leveraging sensor technology, data analysis, and cloud computing to optimize water usage in farming. An important advantage of this system is its integration of Precision Agriculture (PA) principles with cloud computing infrastructure. With this integration, farmers could gain real-time access to critical data and understandings through the user-friendly cloud-based interface. These allow them to remotely monitor the system, gather soil data, and adjust irrigation methods as needed, ultimately leading to increased crop yields and increased income. Recent studies have shown that IoT technology is potential in supporting water-saving approaches for paddy cultivation through IoT-powered and or Automated.

Alternate Wetting and Drying (AWD) technology. In the study conducted by Tolentino *et al.* (2021) revealed that AWD with IoT-powered automation could save about 20% of water compared to traditional AWD methods. Similarly, Pham *et al.* (2021) studied an IoT-powered sensors' efficiency in providing precise water measurement in farm trials. Results showed that farmers who utilized a sensor-powered AWD significantly saved 13-20% of water compared to traditional AWD methods. In addition to water conservation, integrating IoT and automation technology in AWD could reduce irrigation energy costs by 25% and moderately boosted yields between 2-11%, highlighting its cost-effectiveness and productivity value in agricultural production. A study by Rana *et al.* (2023) analyzed an automated AWD system, with minimum growth and yield component differences between conventional, manual AWD, and automated AWD techniques. However, an automated AWD system performed better in terms of water use efficiency (WUE) at 65.20 kg/ha/cm, compared to 52.56 kg/ha/cm with conventional irrigation. It reduced irrigation water consumption by 20%, saved labour, and supported environmentally friendly farm practice.

Recent research reveals improvements in both practical automation and sophisticated modeling techniques. Alce *et al.* (2024) developed a new, technology-intensive automated AWD system. Innovation in such a system comes in its automation of the AWD function through real-time information collection through water level and moisture sensors in the ground. With such automation, scheduling irrigation precisely during cropping, in lieu of less reliable traditional approaches and with changing variable paddy growing cycles, is eased. Integration with modern technology such as SMS messaging, a low-power wide-area network (LPWAN) for distant access and administration, and an IoT dashboard for visualization permits farmers to obtain significant information regarding water use and state of the ground, allowing for information-guided decision and continuous improvement.

Complementing such a practical application of technology, Dela Cruz *et al.* (2022) addressed a significant lack in present irrigation models which is the coupled surface-subsurface flow simulation. Considering that the conventional methods have difficulty in representing complex paddy field water behavior through isolating and working with individual surface and subsurface flows, a new coupled model with Python script codes were developed.

Coupling is a vital development, allowing for a more real simulation of water flow in paddy system and direct application in optimizing AWD methodologies. Strength in such a model comes through its thorough testing and calibration with field information acquired through wireless sensors, proving its accuracy and reliability. In addition, such work provides significant information regarding impact of plow pan behavior in controlling soil-water flow, enriching an overall picture of paddy system behavior. Most importantly, such a model addresses a weakness in present approaches, namely in simulating paddy field boundary conditions.

In addition to these research observations, Kumar *et al.* (2024) developed an electronic sensor-based computerized AWD system that demonstrated significant improvement over traditional continuous ponding methods. Irrigation water productivity increased to 6.15 kg $ha^{-1}mm^{-1}$ compared with 3.06 kg $ha^{-1}mm^{-1}$ for the control, and total water productivity increased to 4.80 kg $ha^{-1}mm^{-1}$ from 2.63 kg $ha^{-1}mm^{-1}$. Automatic water savings of 36% were achieved, highlighting its efficiency and sustainability in paddy cultivation. Collectively, these studies demonstrate the revolutionizing impact of computerized AWD systems in achieving water-saving and sustainable paddy production globally.

As indicated in Tolentino *et al.* (2021), IoT technology can save 20% more water through automation of AWD in contrast with traditional methods utilized in the past. Besides, IoT effectiveness in enhancing AWD techniques through correct water measurement was also studied in experiments conducted in farms (Pham *et al.*, 2021). Results showed that the use of IoT enabled sensors significantly improves water management. Farmers using sensor-based AWD achieved 13-20% additional water savings when compared to farmers utilizing manual AWD methods. The technology not only saved water, but also lowered energy costs of irrigation by 25%, further establishing its cost effectiveness. It also led to moderate yield improvements of 2-11%. Such yield improvement figures further bolster its potential to improve agricultural productivity. However, no considerable variation in the rice yield component between conventional, alternate wetting and drying, and automated alternate wetting and drying irrigation systems was detected according to Rana *et al.*, 2023, and only negligible variation in growth and development was experienced.

A similar work by Rana *et al.* (2023) evaluated an automated alternate wetting and drying (AWD) irrigation for irrigating rice. Variations in growth and development between conventional irrigation, alternate wetting and drying and automated alternate wetting and drying were observed to be minimal. In terms of yield components, no variation in yield components between conventional irrigation, alternate wetting and drying and automated alternate wetting and drying was noticed. In terms of water use efficiency, irrigated crop with automated alternate wetting and drying showed high water use efficiency (WUE) of 65.20 kg/ha/cm and minimum WUE of 52.56 kg/ha/cm in conventional irrigation. Adoption of automated alternate wetting and drying saved 20% water for irrigation in comparison with conventional, reduced labor-intensive interventions and facilitated environmentally friendly rice production. An electronic sensor powered automated AWD developed by Kumar *et al.* (2024) showed significant advantage of automated AWD over conventional continuous ponding. Irrigation water productivity increased to 6.15 kg $ha^{-1}mm^{-1}$ from 3.06 kg $ha^{-1}mm^{-1}$ for control. Total water productivity increased to 4.80 kg $ha^{-1}mm^{-1}$ from 2.63 kg $ha^{-1}mm^{-1}$ under continuous ponding. Automated system saved 36% water; hence, it is efficient and environmentally friendly for producing rice.

These findings validate that sensor-based automated irrigation systems that irrigating with sensors can maximize water use efficiency in AWD approach for rice cultivation.

Overcoming logistical challenges in AWD, such systems represent a breakthrough towards efficient use of water in agricultural. These outcomes underscore the capacity of IoT to refine AWD irrigation. The sensors' ability to monitor water levels with precision empowers farmers to fully capitalize on the advantages of AWD, resulting in substantial water conservation and heightened resource efficiency. The increase in yields and the diminished energy costs further bolster the argument for embracing this technology. These researches highlight how technology can help farmers adjust to climate change and safeguard their livelihoods. The various studies show that investing in AWD systems that use IoT and automation can be economically worthwhile, however, the exact financial gains may vary based on specific situations and local factors. Future studies should examine the potential of integrating technological innovations like automation and IoT to be scaled up and identify the elements that affect whether farmers embrace this technology.

Conclusion

Efforts in mitigating water scarcity particularly for developing nations address conserving water, efficient use, cost savings in producing rice and environmental protection. Practices such as Alternate Wetting and Drying (AWD) responds the effects of water scarcity in terms of food, financial and environmental security, communities, and water. Alternate wetting and drying (AWD) technology is highlighted as a vital method for water conservation in agriculture, particularly in rice cultivation. Studies emphasize its multiple advantages, such as enhanced water efficiency, increased rice production, and economic profitability. AWD optimizes resource utilization by augmenting rice yields and nitrogen efficiency while lessening the need for frequent irrigation. Furthermore, it promotes environmentally sound farming by boosting water productivity and improving nitrogen handling. Combining AWD with organic soil conditioners offers significant benefits, including higher yields, economic benefits, and a lessened environmental footprint. Although beneficial, careful application should be noted because some studies recorded yield decline under stricter AWD regimes.

AWD's capacity to mitigate groundwater overuse and safeguard resources is clear.

Nevertheless, problems to widespread AWD adoption exist, requiring additional investigation and policy measures to ensure agricultural sustainability. Considering how Alternate Wetting and Drying (AWD) affects crop quality, socio-economic elements, and how different rice varieties react is crucial for the success incorporation of the technology into farming practices.

Integrating automations and IoT technologies into smart irrigation systems marks an important advancement in agricultural efficiency and sustainability. Studies reveal that these automations and IoT-enhanced systems refine farming processes by automating tasks and optimizing resource use, thereby boosting overall productivity and efficiency. Through machine learning and IoT integration, smart irrigation systems precisely calibrate water usage, promoting ideal conditions for crop development and yield. The proposed IoT-based systems exhibit impressive precision in automated irrigation, reducing the need for human involvement while optimizing water conservation and efficiency. IoT-powered models facilitate precise irrigation, enabling effective resource allocation and management. Studies focusing on assessment highlights the ability of precision irrigation to enhance the efficient use of water while maintaining crop productivity, underscoring the crucial function of the Internet of Things (IoT) in advancing sustainable farming. The combined results of these investigations highlight the revolutionary influence of intelligent irrigation systems, powered by IoT, in reshaping agricultural methodologies. These systems enable accurate distribution of resources, reduce the need for manual labor, and eventually boost crop yield while promoting environmentally friendly practices. Nevertheless, subsequent research needs to investigate the feasibility of expanding this method and identify the factors that influence farmers' adoption of this technology.

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