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Review Article

The Effect of Irrigation Techniques on Sustainable Water Management for Rice Cultivation System - A Review

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Abstract

Rice serves as a fundamental sustenance for approximately half of the global population, particularly in Asia. Nevertheless, the cultivation of rice demands a substantial water supply, and the challenges associated with water deficits have been exacerbated by irregular rainfall patterns induced by global warming. Consequently, there is a critical need to reassess irrigation techniques to effectively tackle these issues. In this comprehensive review, the Preferred Reporting Items for Systematic Reviews and Meta-analysis (PRISMA) method was employed to systematically explore literature on irrigation techniques aimed at fostering sustainable water management in rice cultivation systems. The primary components of the framework encompass water consumption and water-related characteristics, soil-related characteristics, and plant-related characteristics, encompassing relevant components and indicators. Two alternative irrigation methods, namely alternate wetting and drying (AWD) and saturated soil irrigation (SSI), have been proposed to enhance water use efficiency (WUE) in rice cultivation compared to traditional continuous flooding (CF). These alternative irrigation methods do not adversely affect rice yield, both quantitatively and qualitatively. Furthermore, these alternative irrigation approaches have the potential to mitigate greenhouse gas (GHG) emissions, particularly methane emissions, in rice production. This review underscores the significance of data on alternate irrigation systems, providing valuable insights for researchers and policymakers in formulating strategies that align at every level for practical implementation. This is crucial as it is relevant to multiple organizations and stakeholders. Moreover, in the face of inclement weather conditions resulting from climate change, the study's findings indicate that research on farmers' adaptation, plant stress, and resilience within the rice cultivation system is still in its nascent stages. This highlights the pressing need for further exploration and advancement in these areas to develop effective strategies for coping with the challenges posed by climate change.

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Introduction

Water plays a vital role in the growth of plants, from the germination of seeds to the development of foliage and reproductive stages, directly impacting the yield of various crops, especially grains [1–3]. However, climate variation has resulted in unpredictable rainfall patterns, exacerbating drought issues. [4–7]. Constructing large dams is a challenging approach, as the benefits may not outweigh the drawbacks. [8–9]. Hence, it is crucial to reevaluate the effectiveness of irrigation systems in agriculture, considering factors such as economic viability, social and environmental sustainability, and the Sustainable Development Goal indicator 6.4.1, which measures changes in water usage efficiency over time.

Approximately 70% of the world's freshwater consumption is allocated to agriculture, and out of that, around 70% is used for irrigation, with Asian countries using 90% of that water for rice production [10–12]. The prevailing irrigation technique in Asia is continuous flooding (CF). This method involves growing rice in lowland areas where the field is kept flooded, with the water level maintained at approximately 5 to 10 cm above ground level, can be implemented Figure 1, which demands 1 to 3 m^3 of water to produce 1 kg of rice [13–14]. However, CF proves to be inefficient as a significant amount of water is lost through evapotranspiration, seepage, and percolation. In paddy fields employing CF, evapotranspiration (ET) rates vary between 4 to 7 mm per day, while seepage and percolation (SP) rates range from 1 to 5 mm per day in heavy clay soils and can reach up to 30 mm per day in sandy and sandy loam soils [15].

To promote water conservation in lowland (paddy) irrigated fields, two effective water-saving technologies can be implemented [16]: alternate wetting and drying (AWD) and saturated soil irrigation (SSI). With AWD, irrigation water is applied to flood the field for a certain number of days after the standing water has disappeared, resulting in alternating flooded and non-flooded conditions. On the other hand, SSI involves keeping the soil as close to saturation as possible and applying irrigation to maintain a floodwater depth of approximately 1 cm per day or shortly after the standing water has disappeared (Figure 1).

These alternative approaches have the potential to reduce water usage by 15 to 30% compared to CF [17]. AWD irrigation, in particular, has emerged as a well-established method for conserving water in rice production. It can save water by approximately 15 to 57% more than CF irrigation, making it a cost-effective and efficient choice. However, AWD is not widely adopted as it is better suited for areas where irrigation water can be controlled and when significant yield increases are not the primary objective. It is worth noting that under certain circumstances, AWD may even lead to yield reduction [18–22]. Moreover, AWD demonstrates lower methane (CH_4) emission rates compared to CF irrigation, contributing to environmental sustainability [23].

Another water-saving practice, SSI, offers the potential to enhance water productivity. The rice yield achieved through SSI technique does not show a significant difference compared to CF irrigation [24–26]. However, it is important to acknowledge that SSI requires more time and energy compared to CF irrigation [23–25].

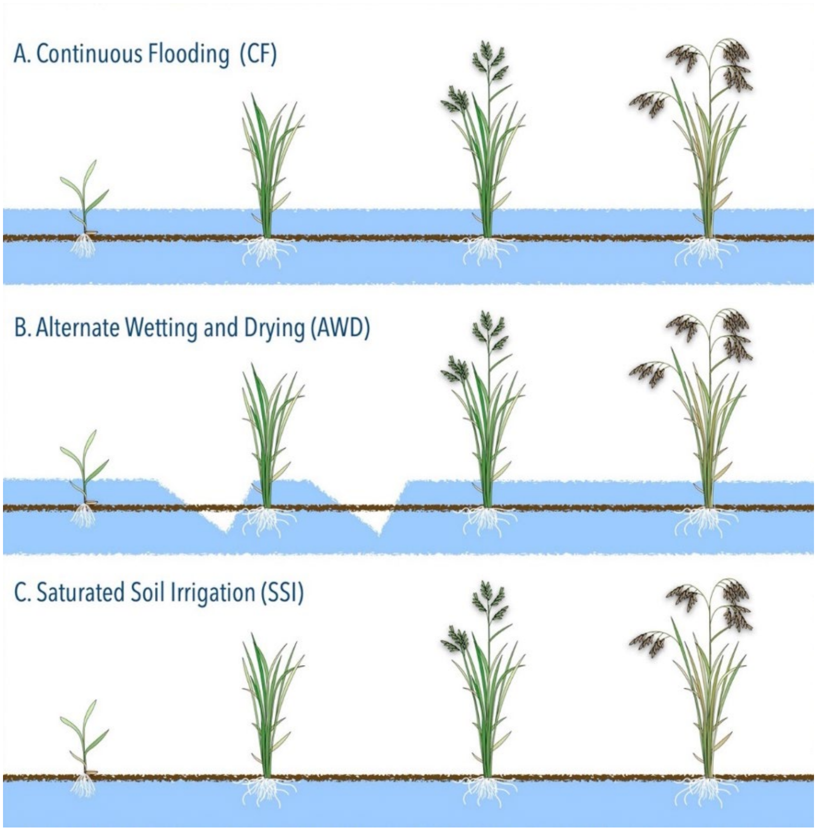

Figure 1 Popular irrigation methods in rice cultivation system [16].

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Additionally, the water footprint serves as an indicator of the efficiency of water usage and its overall impact within the cultivation system. In the case of rice cultivation, the water footprint associated with CF irrigation is approximately 1.6 x 103 m^3 per ton of grain, surpassing the water footprint of other arable crops like wheat, corn, barley, and sugar cane [27]. To improve the efficiency of rice production, ongoing efforts are focused on the development of various cost-effective technologies, with AWD irrigation being a notable example.

This review focuses on the impact of three rice irrigation techniques. Specifically, it examines the dimensions and components of rice irrigation that have been studied in the past decade, with a particular emphasis on sustainable agriculture. Our goal is to assess the effects of irrigation techniques, taking into account not only water usage efficiency but also factors such as greenhouse gas (GHG) emission, absorption of essential elements and heavy metals, yield, yield component, rice physio-logical trait, grain quality and economic returns. Through a critical evaluation of existing research gaps and scope along with policy implications and scope for our future studies.

Methods

This systematic review was prepared by the modified framework [28]. The framework approach incorporates the Preferred Reporting Items for Systematic Reviews flowchart, as outlined by Liberati et al. [29], which serves as a guide-line for conducting systematic reviews. Initially, two scientific databases namely Science Direct and Scopus, were utilized to select eligible studies written in English, focusing on rice irrigation and water use efficiency. The search terms used included “rice” and “water usage efficiency” and “irrigation method” or “AWD” or “saturated”. Inclusion criteria involved journal articles written in English and published in peer-reviewed journals. To ensure comprehensive coverage, the reference lists of all selected papers were examined to identify additional relevant materials, which were then included in the final list for data extraction.

A total of seventeen studies were selected for systematic review based on the search criteria process, following the PRISMA protocol. The initial search yielded a total of 564 results across the databases, with 415 results from Science Direct and 149 results from Scopus. The studies included in the review span the years 2006 to 2021. After removing duplicates, 334 articles underwent title and abstract screening. From this screening, 96 articles were deemed eligible for full-text review, and ultimately, 17 articles were included in the final report, as shown in Figure 2.

In this review, the search terms used were “rice” and “water use efficiency” and “irrigation method” or “AWD” or “saturated”. Articles were identified through searches conducted in abstract, title and keyword. The modified framework employed in this review consists of three stratified levels, as outlined in Table 1. At the highest level, dimensions were considered, which encompass water consumption and water related characteristics, soil related characteristics and plant related characteristics. Under the dimensions level, components were examined, which encompassed the common effects of irrigation techniques on each dimension. For example, WUE and GHG emission were examined under the dimension of water consumption and water related characteristics, elements absorption under the dimension of soil related characteristics and yield, yield components, physiological trait, grain quality and economic returns under the dimension of plant related characteristics. Additionally, indicators were utilized as measurable factors to assess the effects of irrigation within specific indicators at the specialized level of the framework.

As the investigation progressed, the framework was developed and expanded iteratively. Initially, a comprehensive description of the studies included in the review was provided. All reported outcomes and primary data from validated experiments were incorporated into the analysis. Subsequently, the data was reevaluated using the revised framework to identify research gaps and inform the development of government policies aimed at reducing water usage in rice farming for the establishment of sustainable water supply.

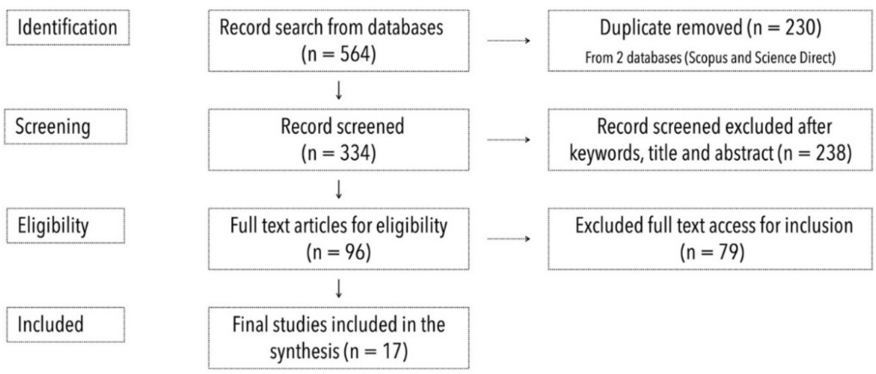

Figure 2 Selection of studies for systematic review based on PRISMA protocol.

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Table 1 The modified framework for data analysis sustainable irrigation system in rice cultivation

Dimensions	Components	Indicators	References
Water consumption and water related characteristics	Water use efficiency	Water productivity	[30–34]
	GHG emission	CH_4 content NO_2 content	
Soil related characteristics	Elements absorption	Essential elements Heavy metals	[35–39]
Plant related characteristics	Vegetative and reproductive traits	Yield Yield components Chlorophyll content Phytohormones	[19, 34, 40–44]
	Grain quality	Amylose content Protein content 2-AP content GABA content	
	Economic returns	Cost Income	

Results

Different water management practices, including CF, AWD, and SSI, have a significant impact on water efficiency in rice cultivation. CF is a popular irrigation technique due to its cost-effectiveness and weed prevention capabilities. However, it is associated with low WUE and contributes to the emission of GHGs, especially methane. On the other hand, AWD is a commonly adopted alternative method that can be divided into moderate AWD and severe AWD. Moderate AWD involves irrigating when the soil water potential ranges from -15 to -25 kPa or when the water level is maintained 15 to 20 cm below the ground surface. Severe AWD, on the other hand, requires irrigation when the soil water potential falls below -25 kPa. AWD shows promise in improving both WUE and GHG emissions in rice cultivation. Another intriguing option is SSI, where irrigation water is applied until the soil reaches its saturation point. This method offers an alternative approach that aims to optimize water usage while minimizing negative environmental impacts.

Moreover, the literature review provides valuable insights into the factors influencing water efficiency in rice cultivation. It highlights the limitations of CF and explores alternative irrigation methods like AWD and SSI as potential solutions to enhance WUE and address environmental concerns in rice cultivation. Moving forward, we can now present the results of the analysis and synthesis of the interrelationships between these three irrigation methods and other factors that impact water resource utilization and environmental effects across three dimensions: water consumption and water related characteristics, soil related characteristics, and plant related characteristics.

1) Water consumption and water related characteristics

1.1) Water use efficiency and water productivity

Water scarcity is a significant constraint in agricultural production, and rice, being a staple crop, requires a substantial amount of water for its cultivation. However, the increasing water demand and the effects of global warming have intensified water scarcity issues. CF or basin irrigation, which is the most widely used method for paddy rice cultivation, has relatively low WUE (Table 2). In comparison to other cereals, rice requires roughly 2 to 3 times as much water for cultivation. Due to their flooded soil surface for almost the whole growing season, rice paddy fields diverge significantly from upland agricultural systems. CF in rice production accounts for more than 45% of total freshwater consumption in Asia. Therefore, the Asia-Pacific CF rice production is expected to face water scarcity on 15 million hectares by 2025 [45–46]. In Asia, where around 90% of rice is grown, the water problem poses a long-term threat to the viability of irrigated rice systems and food security. Therefore, there is a need for the development of more efficient irrigation methods [47–49]. AWD has gained popularity as a water-saving irrigation technique, offering increased WUE by reducing water input while potentially increasing grain yield. Several countries, including China, Vietnam, India, Nepal, Indonesia, and the United States of America, have successfully implemented AWD system. In AWD, the soil is not maintained submerge all the time; rather, it is allowed to drain fora period following the disappearance of the ponded water before being reflooded. AWD is not only a promising strategy for increasing WUE, but it can also regulate plant development, promote plant root vitality, and delay leaf senescence [44, 50].

Table 2 The water consumption and water productivity of 3 irrigation regimes, CF, AWD and SSI [16]

Irrigation regime	Water consumption (mm)	Water productivity (kg m^{-3})
Continuous flooding (CF)	2,869 ± 167	0.9 ± 0.07
Alternate wetting and drying (AWD)	2,091 ± 158	1.4 ± 0.14
Saturated soil irrigation (SSI).	1,382 ± 130	1.2 ± 0.14

The recommended threshold for AWD irrigation is a soil water potential of -20 kPa or maintaining the water level below the soil surface at 15 cm without compromising yield. Subsurface irrigation also exhibits higher WUE compared to surface irrigation [30, 33, 51]. SSI, also known as non-flooding irrigation, is another promising approach for enhancing water productivity in rice cultivation. It suggests that SSI or aerobic rice might represent a feasible decision for water scarcity scenario. SSI's water productivity was almost twice as great as CF's. SSI involves irrigating the field to a depth of approximately 1 cm per day after the standing water has dissipated. Increased water productivity and a significant reduction in wasteful water outflows are possible with SSI [26, 46, 52]. In SSI, efforts are made to maintain soil moisture close to saturation to reduce seepage and percolation. However, this irrigation technique requires careful management to prevent excessive watering [15, 46]. It is important to consider potential stresses and physiological characteristics, such as carbohydrate translocation from stems and phosphate translocation from leaves, when implementing SSI. Some non-flooding irrigation systems have shown significant reductions in vegetative growth, carbohydrate allocation, yield, and yield components [32, 53]. Rice growth is negatively affected by moisture stress, leading to reduced grain yield. Therefore, it is crucial to determine appropriate irrigation thresholds for different rice varieties when implementing water-saving irrigation methods.

In summary, water scarcity poses a challenge to rice cultivation, and more efficient irrigation methods are necessary. AWD and SSI are popular alternatives that can improve WUE while considering specific irrigation thresholds for different rice varieties. These approaches have the potential to address water scarcity issues and enhance rice production.

1.2) Greenhouse gas (GHG) emission

Currently, water-saving techniques are crucial not only for mitigation water scarcity but also for alleviating the impact of both climate variation and climate change. However, the widely practiced irrigation method in rice cultivation, CF, leads to significant water wastage and GHGs emissions, particularly methane. Methane, a potent GHG, plays a substantial role in the chemistry of the troposphere and stratosphere, affecting the composition of ozone, water vapor, hydroxyl radical, and various other compounds. Under anaerobic conditions, methanogenic bacteria decompose organic matter, resulting in the production of methane. Agricultural practices, especially irrigation and organic matter management, can significantly influence methane emissions from rice cultivation [54–56].

Numerous studies have indicated that AWD has the potential to reduce methane emission by approximately 40–80%. However, it has been observed that AWD also leads to an increase in nitrous oxide (NO_2) emissions by 40–160% [33, 57]. This trade-off relationship complicates the assessment of overall GHG impact. Therefore, it is essential to calculate the GHG influence in terms of CO_2 equivalents using metrics such as global warming potential (GWP) and greenhouse gas intensity (GHGI). In comparison to CF, AWD generally reduces GWP and GHGI by 20–30% and 25–30%, respectively [31, 33, 54, 57]. Insufficient data on SSI hinder drawing definitive conclusions about the relationship between irrigation methods and methane emissions. Therefore, this gap in knowledge regarding SSI can be considered a part of our current understanding.

2) Soil related characteristics

The adoption of alternative irrigation methods with an appropriate design is also a growing trend towards enhancing the absorption of essential elements while minimizing the uptake of certain heavy metals, all without compromising the quantity and quality of grain yield.

2.1) Essential elements

In addition to water availability, the choice of irrigation method also has an impact on nutrient availability. AWD has the potential to influence soil physical conditions, such as promoting macropore development and providing a slight improvement in soil mechanical impedance. While AWD does not directly affect soil organic matter or organic carbon supply [58–60], it does increase the availability of nitrogen (in the form of NO_3^-), phosphorus, and potassium in the rhizospheric soil of rice [35]. Furthermore, the implementation of partly aerobic rice system or PARS (periodic aerobic conditions in the soil are produced by water management techniques such as intermittent flooding or AWD) and changes in phytohormone concentrations (increases abscisic acid (ABA) but decreases cytokinin and gibberellin) can enhance the nitrogen use efficiency (NUE) and phosphorus use efficiency (PUE) of rice [36, 61]. Rice cultivated using AWD water management had a PUE that was ap-proximately 21–25% greater than rice grown with CF water management [36]. In the same a direction, AWD water management can boost NUE by 7–33% [61]. A well-implemented AWD strategy does not require significant modifications in nitrogen management, and may allow rice growers to reduce phosphorus fertilizer rates without compromising vegetative growth [36, 61]. However, it should be noted that some available data suggests a decline in rice yield in aerobic rice systems (ARS) over time. ARS involves non-puddled, non-flooded, and non-saturated soil conditions. The decline in yield implies the potential deficiency of nutrients such as nitrogen, phosphorus, potassium, iron, and zinc [62]. This raises concerns about the long-term viability of ARS as a sustainable approach.

2.2) Heavy metals

Soil contains not only essential nutrients for plant growth but also heavy metals, such as arsenic (As) and mercury (Hg), which can be absorbed by plants. Cultivating rice in areas with heavy metal contamination increases the risk of heavy metal accumulation in the grains. However, several reports indicate that AWD irrigation can help alleviate the accumulation of AS and Hg. The levels of As and Hg in rice grains under AWD are generally lower compared to CF, with reductions ranging from 13.7–91.8% for As and 2.7–89.2% for Hg [37, 38, 63, 64]. In comparison to the AWD, the CF promoted as accessibility in the rhizosphere, which boosted as absorption and transport to the xylem in rice via stimulating the expression of silicon transporter genes (*OsLsi1* and *OsLsi2*), but decreasing soil available sulphur and phytochelatins production [37, 64]. Additionally, in the CF-submerged rice fields, anaerobic microbes potentially metabolize the less hazardous inorganic mercury (Hg) into methylmercury (MeHg), which is effectively stored in rice grains [65]. Consequently, using AWD irrigation in rice farming may be a practical and long-term approach to reduce As and Hg contamination in rice, thereby mitigating associated human health risks.

However, it is important to exercise caution when cultivating rice in cadmium (Cd)-contaminated areas. Some studies suggest that cereals under AWD irrigation may potentially accumulate more Cd compared to CF [39]. In contrast to As and Hg, the oxidation of sulphur in Cd sulphide precipitates and the subsequent release of Cd^{2+} into soil solution are two of the many reasons that Cd Phyto availability in the soil increases with soil aeration. Additionally, other factors include the weaker adsorption of Cd^{2+} to manganese and iron hydrous oxides at lower pH values that are typical of aerobic soils, compared to anaerobic soils [66]. Therefore, special attention is needed to manage Cd contamination when implementing AWD irrigation in Cd-affected regions.

3) Plant related characteristics

3.1) Yield, yield component and physiological traits

Water deficit stress poses a significant challenge to rice growth, leading to a decrease in grain production. The impact of water deficit stress on plant growth and development directly affects rice grain output. The reproductive development and canopy expansion are negatively impacted by the decrease in leaf water potential, which results in a considerable loss of yield. The stage of crop development can influence the extent of yield loss, with the panicle development stage being particularly susceptible [67–68]. Therefore, when applying irrigation methods in rice fields, it is crucial to consider the implications of water stress.

AWD, the most widely recognized alternative irrigation method in rice cultivation, has the potential to reduce water consumption without compromising yield. Even if some yield components, such as spikelet fertility and unfilled grain number, are quite vulnerable to a water shortage. Properly implemented AWD does not negatively affect yield and other important yield components such as grain weight, grain number per panicle, percentage of filled grains per panicle, and harvest index. Irrigation thresholds generally in the range from -20 to -40 kPa, depend on the potential of each rice variety. [33, 42, 69, 70]. For example, an International Rice Research Institute (IRRI) experiment conducted in 2006 found that when soil water potential reached the threshold of -60 kPa, the I15 variety did not show a significant difference in yield compared to irrigated rice by CF, while rice varieties H5 and I4 achieved a soil water potential threshold of -30 kPa. Rice varieties H10 and I2 had optimal soil water potential and reached a threshold value below -30 kPa [71]. In addition, harvest index (HI), leaf area index (LAI), leaf elongation rate on the main tiller, chlorophyll content, biomass, root weight, and productive tillers of rice under appropriate AWD are not significantly lower than those under CF [19, 41, 51, 72].

Phytohormones, which play a crucial role in plant responses to environmental conditions, exhibit diverse responses to AWD. AWD and CF have no effect on auxin (indole-3-acetic acid; IAA) cytokinins (zeatin riboside, ZR; isopentenyl adenine, iP) and gibberellin (GA3) content. However, AWD leads to higher levels of abscisic acid (ABA) compared to CF. The ABA content of rice treated with AWD irrigation (-15 kPa) was 1.4 – 1.8 times higher than that of CF When the concentration of ABA in the rice plant increases under drying soil conditions, the rate of filling of the spikelets and the remobilization of assimilates stored in the vegetative tissues in the grains occurs. Ultimately, it might also decrease stomatal conductance, which would increase grain weight in the final result [42, 73].

3.2) Grain quality

In addition to yield, irrigation management has an impact on rice quality, especially cooking and eating related characteristics, such as viscosity, temperature of gelatinization, and the ration of amylose to amylopectin. Since countries have varying preferences for quality, it is quite challenging to precisely describe the quality of rice grains [69]. Irrigation management not only impacts the yield of rice but also influences its quality. The appropriate drying conditions, depending on the desired moisture content, can lead to a reduction in amylose content. Conversely, flood irrigation has been found to increase amylose content while decreasing protein content in rice. However, it's important to note that the variety or cultivar of rice also plays a role in determining the quality of the yield.

Additionally, the findings of the tasting panel generally indicate that the cohesion, softness, color, and brightness of cooked rice are negatively correlated with the amylose content. In terms of starch characteristics, the size of starch granules tends to decrease under certain drying conditions, while the amylopectin short chain length decreases while medium and long chain increase. Additionally, 2-acetyl-1-pyrroline (2-AP), an important aromatic compound in fragrant rice, has been found to be higher in rice cultivated under AWD conditions compared to CF conditions [34, 44, 69].

3.3) Water consumption and economic returns

AWD is widely recognized as a water-saving irrigation system that offers multiple benefits, including reduced irrigation costs and long-term water sustainability. Demonstrations and training courses conducted in Asian countries have consistently shown that AWD can reduce irrigation water usage by up to 29% without significantly affecting yields. In fact, rice crops treated with AWD have exhibited higher water productivity, achieving 1.25 times the productivity compared to CF [74]. Fixed costs and some variable costs—like land rent, fertilizers, crop protection, seeds, soil preparation, nursery, and field management—are comparable throughout the course of this two-year field trial. AWD effectively postpones irrigation, which minimizes overall irrigation frequency and, consequently, water usage when applied to appropriate soils. As a result, irrigation application costs can be reduced by up to 30% [43, 75]. This not only leads to decreased expenses on water pumps and fuel consumption but also contributes to increased incomes for farmers. By implementing the AWD technique, gross returns for farmers can potentially increase by 5% [40, 43].

Another alternative technique, SSI, also offers water-saving benefits. On average, SSI has been found to save around 23% of water consumption with a 1.7 times higher water productivity compared to conventional irrigation methods [76].

Discussion

1) Analyzing knowledge gaps for future research

Based on the evaluation of the articles, several research issues have been identified that can guide future research project. While the data analyzed in this study covers the dimensions of water, soil, and plants, there is still a lack of research in the area of plant stress and farmer resilience (Figure 3). The evaluation of economic and environmental impacts of different irrigation systems provides substantial data, but there is a shortage of physiological data, particularly regarding plant stress. However, considering plant stresses, especially related to drought and oxidative characteristics, are crucial when determining future rice irrigation. Changes in irrigation practices directly affect the water status of plants, emphasizing the need to monitor stress levels when implementing alternative irrigation methods. It is essential for these alternative irrigation methods to be efficient without causing harm. Therefore, effective irrigation techniques, such as AWD and SSI are necessary to address issues such as water status and management, which are impacted by climate change and can hinder traditional cultivation methods, potentially leading to reduced productivity if not addressed promptly.

Furthermore, recent studies in the past decades have revealed the limitations of traditional irrigation techniques in rice fields due to the effectiveness of tools and methods. Overwatering has been necessary to prevent stress on rice crops. However, with the advancements in modern technologies, especially smart agriculture technologies, it is now possible to apply modern devices to optimize water usage and meet the specific needs of rice cultivation. For example, the modern irrigation system (MIS) can minimize the water footprint by more than 29% by measuring data using an in-field weather station to calculate VPD values for use in irrigation decisions [49]. In addition, the promotion of smart agriculture in Thailand also encourages the use of smart sensors to measure water levels, facilitate the decision on AWD. The results of the operation showed that the amount of water used could be reduced up to 30% compared to CF [77–78]. Therefore, current innovations

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in alternative irrigations methods offer feasible solutions to reduce water consumption in rice fields and improve WUE.

2) Sustainability component

The fundamental components of sustainable management approaches typically encompass three key elements: economics, society, and the environment. In terms of economics and resource depletion, both alternative technique, AWD and SSI, have shown the reduction in water consumption while increased water productivity. AWD and SSI have the potential to decrease irrigation water usage by 29% and 23% respectively (Figure 4), while also increasing water productivity by 125% and 172% respectively (Figure 4). These finding demonstrate that alternative irrigation methods, when implemented appropriately, can reduce water requirements without compromising yields. Consequently, it can be inferred that "the main cost of fuel consumption for water pumping can be reduced, leading to improved farmer income". Additionally, the partially aerobic rice system (PARS) employed in both AWD and SSI can enhance the rice plant's nitrogen and phosphorus utilization efficiency. This has significant implications as it may reduce the need for fertilizers, which is a major expense for farmers. As a result, alternative irrigation methods have the potential to address the demand for fertilizer and contribute to cost savings.

In terms of the ecological component, implementing AWD in paddy fields may result in a reduction of approximately 38% in methane emissions compared to CF (Figure 4). However, there is still a lack of data on methane emissions from paddy fields treated with SSI. It has been demonstrated that the availability of oxygen in the soil has a significant impact on methane generation, with anaerobic conditions promoting its production [79]. Therefore, it can be observed that alternative irrigation methods, which promote higher levels of oxygen in the soil, have the potential to decrease methane emissions in rice fields. However, it is important to consider the estimation of other GHG emissions for AWD or aerobic irrigation as well.

Regarding the social component, traditional watering methods are still widely used by farmers due to their convenience in preventing dehydration and effectively controlling weeds in rice fields. Therefore, it is necessary to encourage farmers to prioritize environmental considerations and demonstrate that alternative irrigation methods do not adversely affect yields. In order to achieve a sustainable and environmentally-friendly transformation in rice production, it is important for the government to promote awareness and understanding of this crucial issue.

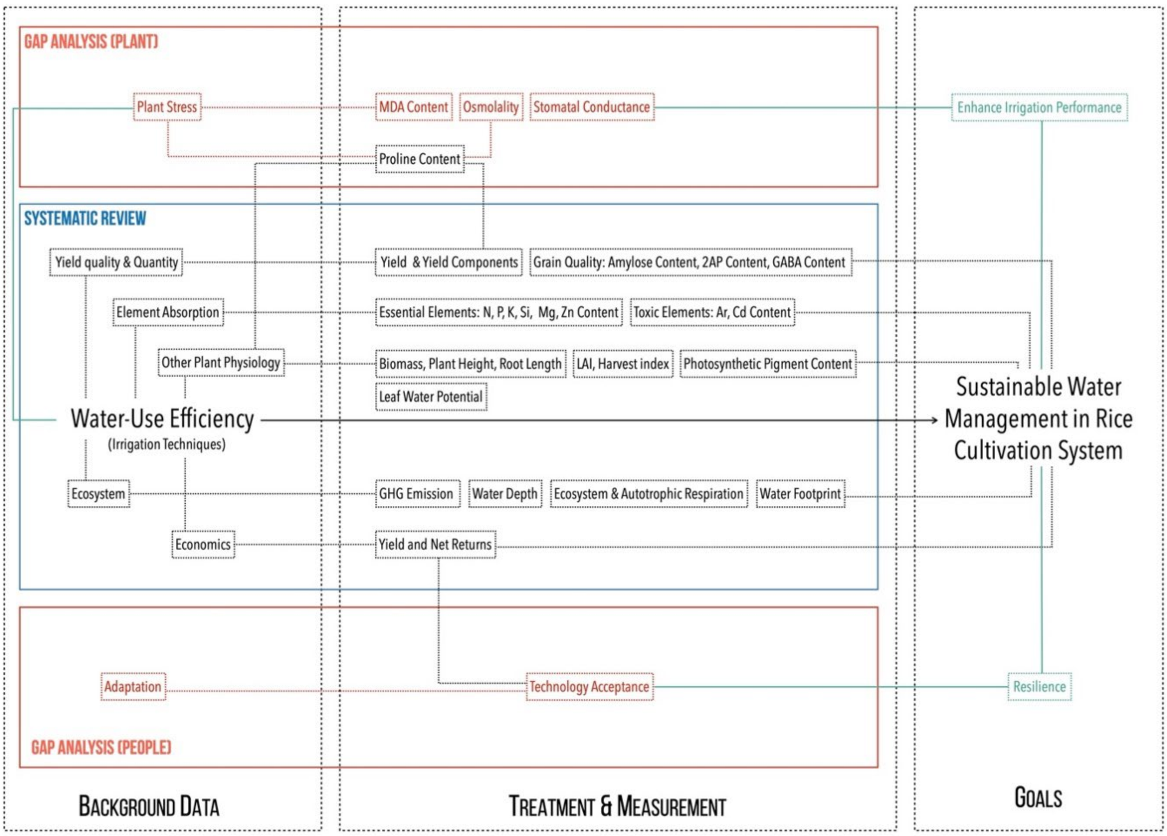

Figure 3 Framework of irrigation system in rice cultivation, research gaps and scope for future studies.

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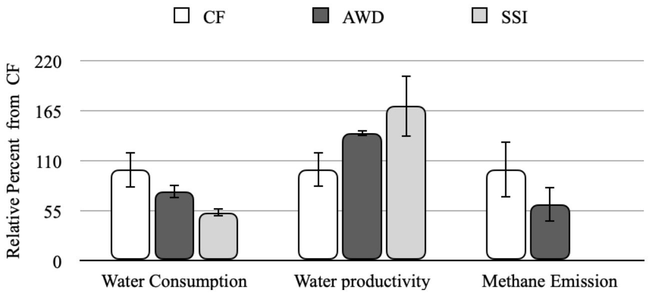

Figure 4 Percentages of water consumption, water productivity and methane emission of AWD and SSI compare with CF [25, 33, 80].

3) Policy implications

The framework for irrigation techniques is built upon the intersection of six components: WUE, GHG emissions, nutrient absorption, yield and yield components, grain quality, and economic returns, as indicated by the findings and discussions above. Due to the variations in plant physiology and environmental factors within an economy, specific water policies are necessary. One key finding from our research is that efficient water use cannot be achieved unless all components are adequately addressed. Climate change, as an external influence, necessitates the adoption of highly efficient alternative irrigation methods that reduce water usage, minimize environmental impacts, and pose no harm to plants. Hence, comprehensive data on the impact of alternative irrigation technique on each component and their interactions are crucial for making macro-level policy decisions and implementing alternative irrigation systems.

Considering the current state of irrigation methods in rice fields, CF remains a popular technique due to its cost-effectiveness, convenience, and weed prevention benefits. However, CF is less efficient and generates significantly higher GHG emissions compared to alternative techniques such as AWD or aerobic irrigation. The development of CF in rice fields to reduce GHG emissions is challenging due to the anaerobic conditions caused by flooding, which directly contribute to methane emissions, a major GHG in rice fields. Consequently, both alternative irrigation techniques, AWD and aerobic irrigation, prove to be more efficient and environmentally friendly than CF. Therefore, it is crucial to promote these alternative irrigation methods through policy implementation in water management, especially in the agricultural sector, which has high water demands and limited water resources.

Even though alternative irrigations are more effective and environmentally friendly than that of CF, CF irrigation is still widely used due to its familiarity, simplicity of weed control, and economic value—especially in countries that state-sponsored irrigation programs are in place. Consequently, it becomes crucial for the government to raise public awareness about the importance of water efficiency, environmental friendliness, and the risks and crises resulting from global warming. These are all aspects that should be communicated and taught to farmers.

To instill confidence in farmers, the government needs to establish in-field demonstrations of alternative irrigation methods, showcasing that reducing water usage in rice fields does not have a negative impact on yields. Additionally, it is essential to provide encouragement, support, and incentives for farmers to adopt these methods in practice.

Implementing alternative irrigation techniques not only reduces water consumption at the field level but also aids the government in effectively managing water resources as a whole, particularly during drought years when water supplies are insufficient for all activities. Furthermore, alternative irrigation methods contribute to the achievement of Sustainable Development Goals (SDGs) by effectively reducing GHG emissions in another way.

Conclusion

Considering the impact of global warming, it is imperative to incorporate effective irrigation methods in rice cultivation that not only consider the water requirements of plants but also prioritize factors such as WUE, physiological processes, and resilience in stressful situations. The review conducted has demonstrated that AWD and SSI are viable alternative irrigation methods that can improve WUE in rice fields.

Furthermore, numerous studies on AWD have highlighted additional benefits, including reduced GHG emissions, particularly methane, enhanced nitrogen and phosphorus use efficiency, and decreased accumulation of contaminants like arsenic (As) and mercury (Hg) in the grain. AWD has also been found to be a delicate and effective irrigation method that does not compromise grain production and quality, while also being economically feasible.

Additionally, the interlinkage between research on rice irrigation techniques, such as plant stress, farmers' adaptation, and their capacity for resilience, is still in the early stages of development within the context of rice cultivation systems.

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