Water-Saving Technologies for Rice Production

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In the face of the negative impacts of climate change and the accelerated growth of the global population, precision irrigation is important to conserve water resources, improve rice productivity and promote overall efficient rice cultivation, as rice is a rather water-intensive crop than other crops. Water-saving technologies for rice cultivation are varied and can be classified into three groups: water-saving irrigation systems; water-saving irrigation methods and water-saving agronomic practices.

water conservation technologies irrigation water productivity

1. Water-Saving Irrigation Systems for Rice Production

The surface irrigation methods are commonly used for rice production. However, the costs and advantages of producing rice under aerobic conditions are an alternative to flooding, which is an efficient technique to decrease weeds and other pests but uses too much water [1][2]. According to several authors [3][4][5][6], majority of the land is irrigated using surface methods in which water is distributed over the field via overland flow. However, rice crop can also be grown under drip or sprinkler irrigation systems to improve water and fertilizer use efficiency, because the flooding practice involves a higher water footprint for rice production than any other crop in the agriculture [7].

1.1. Surface Irrigation Methods for Rice Production

Despite their low efficiency and uniformity, due to poor design and water management in other irrigation methods, surface irrigation methods are the most used in the world [8][9]. Surface irrigation methods, including basin irrigation, border irrigation, and furrow irrigation are characterized by inefficient irrigation, leading to wastage of water, water logging, salinization and pollution of surface and ground water resources [4]. In order to make rice cultivation on gravity-fed irrigated schemes sustainable, several studies focused not only on the water-saving practices, but also on the furrow irrigation.

Hardke and Chlapecka [10] showed that furrow irrigated rice production has been increasing in recent years, from less than 1% in 2015 to 10% in 2019 in US due to easy crop rotations, and decrease in time and costs compared to flood irrigated rice production. According to Stevens et al. [11], furrow irrigation method is better than conventional flood irrigation for growing rice with less water and labor and it contributes to reduced arsenic content in irrigated rice grain. Other studies revealed that the yield component and rice yield were low for furrow irrigated rice whereas arsenic concentration is high in rice for flood irrigation [12][13].

Several authors [1][14] showed that furrow irrigation system compared to conventional irrigation has several advantages:

- It can significantly reduce irrigation water losses rate through seepage, evaporation, and evapotranspiration;
- It can reduce harmful materials, such as ferrous ion;
- It can reduce the rice field humidity and enhance gas transport in the soil and light penetration;
- It can reduce rice diseases and consequently increase leaf vitality; and
- It can increase grain yield and water productivity.

On the contrary, Beesinger et al. [15] and Deliberto and Harrell [16] indicate that furrow irrigation system, compared to flooding irrigation, has huge disadvantages, such as the following:

- row rice is not easily made;
- water management uniformity is more difficult;
- fertilizer management uniformity is more difficult;
- weed control is more difficult;
- disease potential is greater; and
- harvest problems are increased in deep furrows if the rice lodges.

Surface irrigation system is subject to several criticisms due to its low efficiency and high water wastage and thus alternative new practices are encouraged to enhance water efficiency and gain both economic and environmental benefits [5]. Due to the high water levels in paddy fields, flood irrigation requires a lot of labor, and the farmer often uses a manual device to control the input and output flow [6]. However, in a study, Lee [17] demonstrated that flood irrigation can be sustainable if it is automated. He contends that the automatic irrigation system can be adequate for water supply automation and sustainable water management and can benefit farmers in saving water and reducing labor demands. An automated system will allow the farmer to control flows, volumes, and water levels in the fields using a special website which controls the gate directly, if necessary, or by configuring the irrigation program in accordance with his agronomic methods [6].

1.2. Drip Irrigation System for Rice Production

Drip irrigation is almost non-existent in rice production systems. Very few previous studies focused on drip irrigation of rice crops, yet it is possible (**Table 1**). For Meher et al. [18], using drip irrigation technology in rice farming is the best way to increase productivity while using the least amount of water possible to produce the highest yields, decrease the cost of irrigation water in rice farming compared to the conventional methods, and reduce the overall water consumption of rice crops to levels that are biologically sound.

According to Parthasarathi et al. [2], drip irrigation improved the aerobic rice yield by 29%, increased water saving efficiency by 50%, and consequently increased water productivity, favored the root oxidizing power, canopy photosynthesis and dry matter partitioning. Studies on reducing pressure on underground water under projected climate due to continuously depleting aquifers came to the conclusion that drip irrigation systems offered real benefits for significant savings in irrigation water and energy as well as an increase in nitrogen use efficiency and net income [19]. Rao et al. [20] too showed that the drip irrigation system for rice production was more efficient than conventional paddy cultivation under continuous flooding in terms of enhancing water productivity and saving water energy.

In addition, drip irrigation for rice production has enormous agronomic (e.g., reduction in fertilizer use, reduction in leaching of fertilizers, reduction in diseases and pests, weeds control and mulching), economic (e.g., power saving, reduction in manpower and labor) and environmental (e.g., water use reduction, greenhouse gas emission reduction, arsenic uptake and improved rice quality) advantages [21]. He et al. [22] demonstrated that drip irrigation has greater water saving capacity, lower yield and more economic benefit gaps compared to furrow irrigation and flood irrigation.

Research carried out since 2008 on drip irrigation for rice cultivation (both surface drip and subsurface drip systems and fertigation) showed that rice yields and yield component as well as fertilizers use efficiencies were higher compared to the conventional methods [23]. According to Samoy-Pascual et al. [3], drip irrigation is the greatest alternative for minimizing irrigation water usage and boosting water productivity while growing aerobic rice without using as much water as surface flooding, and still having a comparable yield and financial return. On the contrary, though drip irrigation system improved water productivity, it decreased paddy yields [24].

However, the subsurface drip irrigation performed better than the surface drip irrigation system in terms of rice growth, physiology, and yield [2]. Among the three irrigation systems (drip irrigation, flood irrigation and sprinkler irrigation), Bansal et al. [25] argued that the drip irrigation method significantly increased rice grain yield and water use efficiency. In spite of their benefits, innovative irrigation technologies, such as drip and subsurface drip irrigation, are expensive and need greater technical expertise; as a result, they are rarely used and are typically seen as last-minute fixes [26].

1.3. Sprinkler Irrigation System for Rice Production

Research conducted in the USA on rice production under center pivot irrigation showed that sprinkler irrigation can be an alternative to flooding and would improve water use efficiency and soil water tension [9][27]. According to Parfitt et al., rice grain yield, fertilizer use efficacy (FUE) and water use efficacy (WUE) are high for sprinkler-irrigated rice than for rice grown in flood-irrigated lowland. In addition, sprinkler irrigation system, compared to flood irrigation, significantly reduced arsenic in the harvested rice grain [28]. Similar to this, Alvarenga et al. [29] and Spanu et al. [30] reported that rice production that has successfully switched to sprinkler irrigation from the traditional flooding system can save water and reduce the buildup of arsenic and cadmium in the rice grain, thereby allowing to produce safe rice in soils where traditional irrigation might only result in the production of inedible rice.

However, Moreno-Jiménez et al. [31] demonstrated that even though, as compared to flood irrigation, sprinkler irrigation saved water, increased organic C in soils, and decreased both inorganic and organic arsenic content, it significantly increased cadmium content in rice grain which is a cause of worry. Costa Crusciol et al. [32] showed that sprinkler irrigation system improved the physiological quality of rice seeds produced under upland conditions by reducing water deficiency during the seed development stages. Moreover, sprinkler irrigation facilitates greater weed control as compared to the flood irrigation system [33]. In the same way, even when employing cultivars created for flooded conditions, proper management of a sprinkler-irrigated system can retain high levels of output, minimize irrigation water use, and raise soil water tension, which is shown by a drop in plant heights [34]. In contrast, when compared to flood irrigation, rice growth was poor under sprinkler irrigation, likely as a result of decreased root activity close to the soil surface due to frequent intervals of soil drying [35]. Studies conducted on rice production under sprinkler irrigation are shown in **Table 1**.

Table 1. Previous studies on rice production under sprinkler irrigation system and its influence on water saving.

Location	Impact on Irrigation Water Use, and Rice Yield	References
Arkansas, USA	This study showed that two rice cultivars grown under center pivot irrigation produced high yields (8.31 Mg/ha in 2009 and 8.2 Mg/ha in 2010), with an irrigation water use efficiency of 2.0 kg/m^3 in 2009 and 1.6 kg m^3 in 2010. Rice cultivation with center pivot irrigation required a total irrigation depth of 414 mm, whereas flood irrigation for rice required depths of 1168 mm.	Vories et al. [9]
Arkansas, USA	Researchers have shown that the high-to-low order of total continuous flooding had a greater impact on rice grain content than intermittent flooding or spray irrigation, although neither had a significant impact on production.	Stevens et al. [28]
Spain	In this study, it appears that sprinkler irrigation, compared to flood irrigation, saved more water, increased soil organic C, and decreased both inorganic and organic arsenic concentration in grain.	Moreno-Jiménez et al. [31]
Selviria-MS, Brazil	Field studies conducted in 1994/1995 and 1995/1996 came to the conclusion that water levels ranging from 0.5 to 1.5 times the rice crop coefficient, supplied through sprinkler irrigation system provide better conditions for producing rice seeds of upland cultivars with higher physiological quality.	Costa Crusciol et al. [32]
Capão do Leão, Brazil	According to this study, chemical weed management using herbicide selectivity is more effective with sprinkler irrigation than flood irrigation.	Helgueira et al. [33]
Leão, Rio Grande do Sul, Brazil	Scientists found that a soil water tension of 10 kPa was sufficient to control spray irrigation in rice, particularly during the reproductive stage.	Pinto et al. [34]
Griffith, Australia	The amount of water used for sprinkler irrigation generally appeared to be adequate to meet the crop’s evapotranspiration requirements, but the plants may have experienced moisture stress in the intervals between irrigations since data from the soil matric potential at 100 mm revealed little water stress in sprinkler irrigation during the vegetative stage.	Humphreys et al. [35]
Monoo, Pakistan	Study conducted during 2002–2004 projected that sprinkler irrigation increased rice output by 18% while using 35% less water than the	Kahlown et al. [36]

Location	Impact on Irrigation Water Use, and Rice Yield	References
	conventional irrigation technique and revealed that adopting sprinkler irrigation for rice is a financially viable choice for farmers.	
Tamil Nadu, India	A field experiment carried out in 2013 and 2014 revealed that sprinkler irrigation used the least amount of irrigation water (329.2 mm and 308.7 mm) and surface irrigation used the most (413.6 mm and 428.1 mm) resulting in water savings of 23.1% and 25.4% in 2013 and 2014, respectively.	Kumar et al. [37]
Rio Grande do Sul, Brazil	Experiments conducted over two years (2012–2013) revealed that sprinkler irrigation used 48% less water than flood irrigation while also reducing water stress and improving the physical and chemical characteristics of the soil.	Pinto et al. [38]
Sardinia, Italy	Field studies conducted between 2002 and 2006 showed that irrigation water used for rice cultivation utilizing sprinkler irrigation was approximately 6500 m^3/ha (650 mm).	Spanu et al. [39]
Arizona, USA	Authors indicated that flood irrigation used a total of 589 mm of irrigation water, whereas pivot irrigation used 470 mm, resulting in an irrigation water use efficiency of 1.7 kg/m^3 for flood irrigation compared to 2.1 kg/m^3 for pivot irrigation.	Vories et al. [40]
India	In this review, the author showed that micro-irrigation (drip and sprinkler) potentially contributes to irrigation water savings, but decreases rice yield.	Mandal et al. [41]
Edirne, Turkey	The results of this study over the course of three years (1991–1993) revealed that while sprinkler irrigation produced lower yields than continuous flooding, water savings rates ranged from 12.3 to 43.1%.	Cakir et al. [42]
Texas, USA	Though it reduces irrigation water use, sprinkler irrigation does not seem to be a practical substitute for traditional flood irrigation, according to the authors, because it decreased plant performance (height by 0.09 to 0.28 m and average yield by 20% to 28%).	McCauley [43]
Missouri, USA	According to this study's findings, sprinkler irrigation uses 28% less water than conventional flooding.	Stevens et al. [44]

Although experiments on rice production under micro-irrigation systems (drip irrigation and sprinkler systems) are promising, traditional surface irrigation with continuous flooding practices and significant water consumption remains widely dominant in rice cultivation for a number of reasons [45][46][47]. First, rice cultivation under surface irrigation is an ancestral practice and abandonment of this practice is constrained by socio-psychological barriers [48]. Second, surface irrigation systems are more accessible to rice farmers, especially small-scale farmers, given the requirements of the micro-irrigation systems (high costs, unavailable skills and advanced knowledge). Finally, paddy grain yields are low under micro-irrigation systems compared to surface irrigation [24][41]. In view of this situation, the alternative is to develop and adopt irrigation practices that improve water use efficiency without affecting the yield.

In fact, water-saving practices have a positive impact on (i) the environment by conserving water resources and reducing greenhouse gas and (ii) the economy by increasing fertilizers' use efficiency, agricultural productivity, reducing energy, etc. [49][50]. Previous studies have shown that compared to continuous flooding, all water-saving practices allow for sustainable rice production [51]. According to research [50][51][52][53][54], there are multiple water-saving technologies, including alternate wetting and drying (AWD), soil water potential (SWP), non-flooded mulching cultivation, aerobic rice system (ARS), efficient irrigation regime (EIR), saturated soil culture (SSC), field water level (FWL), intermittent drainage (ID), leaching and flushing methods (LFM), conventional flooding-midseason drainage-flooding irrigation (FDF), etc. The most popular water-saving technologies developed for rice production systems is the alternate wetting and drying (AWD) [45][47]. Islam et al. [45] reported that, according to several authors, AWD entails intermittent irrigation events with intervals of non-flooding, wherein the water level drops below the soil surface between each irrigation, and this saves irrigation water by a range of 7–33% without significant impact on yield compared to conventional flooding. Thus, AWD is a water-saving technology promoted in rice cultivation worldwide due to its effectiveness in improving water use efficiency (**Table 2**).

Table 2. Previous studies on rice production under alternate wetting and drying (AWD).

Location	Impact on Irrigation Water Use, and Rice Yield	References
China	This study has shown that, compared to conventional flooding-midseason drainage-flooding irrigation (FDF), AWD increased WUE by 40% and resulted in maximum grain production (7808.38 kg/ha)	Wang et al. [50]
Tripura, India	According to the authors, 30% of water can be saved using AWD for rice growing under SRI compared to flooding irrigation.	Singh and Chakraborti [55]
Carolina, USA	Study results showed that AWD method lowered irrigation use hours by around 38% while saving irrigation water and boosting energy without noticeably reducing crop yields and revenues.	Rejesus et al. [56]
Wuhan, China	In comparison to other water-saving techniques, the results showed that AWD had the highest average water saving rate of 35.12% and the lowest average yield increasing rate (0.79%)	Zhuang et al. [57]
Fanaye, Senegal	The researchers found that AWD irrigation control at 30 kPa boosted rice production, water use, and nitrogen use efficiency while lowering irrigation applications by 27.3% compared to continuous flooding.	Djaman et al. [58]
Tokyo, Japon	This study, carried out from December 2021 to March 2022, found that AWD utilized 25% less water than continuous flooding	Bwire et al. [59]
Bangladesh	According to this study carried out in 2017, AWD conserved 12% to 24% more irrigation water than continuous flooding.	Albaji et al. [60]
Kushtia, Bangladesh	Authors demonstrated that the AWD technique alone saved 20.2% more field water than flooding irrigation practice, and when paired with plastic pipe, 42% more water was saved.	Hossain et al. [61]
Pingtung, Taiwan	The results indicated that AWD could produce a grain yield that was comparable to the farmers' methods while requiring fewer irrigations.	Tapsoba and Wang [62]
Telangana, India	The experiments (2014 and 2015) demonstrated that the alternate wetting and drying strategy of irrigation resulted in lower water usage of about 795	Rao et al. [63]

Location	Impact on Irrigation Water Use, and Rice Yield	References
	mm to 1180 mm and higher water productivity of 0.52 kg/m^3 to 0.66 kg/m^3, saving 20.2 to 23.4% more water than the submerged irrigation method.	
Tuanlin, China	The three-year (1999–2001) study revealed that irrigation water input was 15–18% lower under alternate water distribution (AWD) than under continuous submergence, and water productivity was higher under alternate AWD.	Belder et al. [64]
Jiangsu, China	In comparison to continuous flooding, AWD or furrow irrigation could boost grain output and water use efficiency (experiment of 2015 and 2016).	Wang et al. [65]
Pingtung, Taiwan	From this experiment in 2016, authors demonstrated that compared to continuous flooding, AWD achieved water savings of 55–74%, with overall water productivity under AWD being 0.35 kg/m–0.46 kg/m^3.	Pascual and Wang [66]

economic complex interactions between agricultural and socioeconomic systems and the absence of institutional backing [47][49][51]. Hiya et al. [67] and Massey et al. [68] reported that intermittent flooding with a reasonable depth of water above ground level would be an alternative to improve water use efficiency in rice production. Afifah et al. [69] indicated that flooding a field to a depth of 1 cm saved 45% of the water used, with significant improvements in WUE, in comparison to flooding at a depth of 5 cm. On the other hand, flooding at a depth of 5 cm and 1 to 3 cm induced similar rice yield, which was higher than rice yield obtained under AWD. In the Philippines, Islam et al. [45] found that seasonal rice water use was 15% lower when utilizing soil water potential (SWP) compared to the water-saving AWD. The studies carried out (2007–2010) by de Avila et al. [64] in Rio Grande do Sul, Brazil, revealed that intermittent irrigation reduced runoff water by 56% and irrigation water use by 22–76%, leading to an increase in water use efficiency of 15–346%. (WUE).

In the same way, other avenues have been explored in previous studies to find alternatives to AWD. Albaji et al. [60] demonstrated that limited irrigation results in a WUE between 13.3 and 13.9 kg/mm, while flooding irrigation provides an average of 12.48 kg/mm. In India, the experiment conducted in 2018 and 2019 revealed that the yield of saturation was comparable to flood irrigation under non-limited water supply while conserving 27% irrigation water [70]. Additionally, through two-year field experiments at Jiangsu, China, Zhang et al. [65] found that shallow water irrigation used the largest amount of water compared to wet-shallow irrigation, but provided a higher yield.

3. Water-Saving Agronomic Practices for Rice Production

Various previous studies focused on good agronomic practices (GAP), such as using drought-tolerant rice variety [71][72], plastic mulching [73], straw mulching [74], organic matter application [75][76], minimum tillage [45], etc., to assess their influence on water saving in irrigated rice production. In addition, water-saving practices are implemented in combination with these good agronomic practices (GAP). Farooq et al. [77] indicated that improved genotype water productivity, different planting times, seeding rates, geometries, improved management of soil fertility, use of mulching to avoid soil evaporation, and weed control will all result in crop plants using water more efficiently.

Moreover, crop canopy is crucial for light interception and light penetration into the soil as well as for plant water consumption (i.e., a dense canopy will shade the soil surface, reduce soil temperature, and therefore limit soil evaporation and reduce crop evapotranspiration) [77]. Results of straw returning utilized to improve soil fertility and crop production showed rice yield enhancement on average by 7.9% and 7.5% and irrigation water use efficiency (IWUE) improvement by 6.3% and 8.3% in 2015 and 2016, respectively [74]. The system of rice intensification (SRI) approach helped to lower the need for irrigation water, resulting in immediate advantages of decreased irrigation water demand [78].

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