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Comparison of Conventional and Water-Saving Irrigation Methods for Improving Crop Growth, Yield, and Water-Use Efficiency

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ABSTRACT

To compare the performance of conventional and water saving irrigation methods in terms of growth, yield and water-use efficiency of rice (Oryza sativa L.), a comparative field experiment was conducted. The experiment was set up in randomized complete block design (RCBD) with three irrigation methods and four replications—conventional continuous flooding (CCF), alternate wetting and drying (AWD), and drip irrigation. Plot size was standardized and all other agronomic factors such as seed rate, fertilizer application, weed and pest control were the same within each treatment. The following data were taken: plant height, number of tillers, root length, days to maturity, biomass production, grain yield and total irrigation water applied, and water-use efficiency was calculated as grain yield/volume of water used for irrigation. Data obtained were analysed by the analysis of variance (ANOVA) and the means of the treatments were separated by Duncan's Multiple Range Test (DMRT) at 5% level of significance. The conventional continuous flood irrigation had the most significant effect on plant height, tiller number, root length, biomass and yield of grain, while consuming significantly more irrigation water than the two water-saving methods. Alternate wetting and drying yielded grain yields statistically identical to those obtained from conventional flooding, but also required 33% less total irrigation water, while drip irrigation required the least total irrigation water but with a small yield reduction compared to conventional flooding. These results suggest that alternate wetting and drying is the most water-saving technique while maintaining the yield, while drip irrigation, in case of severe water scarcity, is the most promising technique for water saving in sustainable crop production systems.
Keywords: water-saving irrigation; alternate wetting and drying; drip irrigation; conventional flooding; water-use efficiency; rice; randomized complete block design

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INTRODUCTION

Freshwater scarcity represents one of the increasing challenges for agricultural production, and the majority of freshwater withdrawals is used in irrigated agriculture, increasing pressure on farmers and researchers to enhance the efficiency of the use of irrigation water (Kang et al., 2017). Rice is extremely water thirsty, and conventional continuous flooding methods are reliable, but result in significant excess water for rice as compared to the physiological water demand, and this has created a longstanding interest in research to develop alternative irrigation methods that reduce water use (Bouman & Tuong, 2001).

Reducing agricultural water use while still producing a satisfactory crop yield requires the development of new water saving irrigation practices, such as alternate wetting and drying (AWD), drip irrigation, and sprinkler irrigation (Tuong et al., 2005). In irrigated lowland rice systems, alternate wetting and drying has been extensively investigated, and has been found in many trials to lead to significant reductions in irrigation water demand with negligible yield losses (Belder et al., 2004; Yang et al., 2007).

The use of drip irrigation has shown to achieve substantial improvements in water-use efficiency for a variety of crops such as cotton, wheat and, increasingly, for aerobic or semi-aerobic rice (Ibragimov et al., 2007; Camp, 1998). Compared to conventional surface irrigation, sprinkler irrigation also provides better water application uniformity and lower conveyance losses, but the water-saving benefits of sprinkler irrigation will vary significantly depending on the crop and local climatic conditions (Zwart & Bastiaanssen, 2004).

Although these water-saving techniques have been proven to have potential, there is still a lack of uniformity in their performance when compared to conventional irrigation, including in terms of trade-offs between water conservation and yield maintenance, thus there is a need to continue evaluation on site and crop specific basis (Carrijo et al., 2017; Lampayan et al., 2015). However, Molden et al. (2010) warned that water productivity improvements under carefully controlled experimental conditions might not directly contribute to water savings at the field scale, and that careful experimental design is necessary for comparative field tests.

Knowing the relative agronomic and water-use efficiency (WE) performance of conventional and water-saving irrigation techniques is critical for making irrigation management decisions in water-limited agricultural areas (Fereres & Soriano, 2007). The present study was thus intended to quantify the various effects of conventional continuous flooding, AWD and drip irrigation in rice on crop growth, yield and water-use efficiency, so as to make recommendations for sustainable irrigation management (Geerts & Raes, 2009).

LITERATURE REVIEW

This has led to a significant amount of research on the agronomic performance of AWD compared to the continuous flood irrigation system in rice. Belder et al., (2004) tested the water-saving potential of irrigation under typical lowland conditions in Asia and reported that under these conditions, AWD approach can save 15–30% irrigation water input without significant reduction in grain yield, thus making AWD a viable water-saving measure for lowland rice. The optimal soil water potential thresholds for the implementation of AWD were studied by Yang et al., (2007) who found that moderate soil drying between irrigation events had beneficial effects not only on conserving water but also on improving root system development and reducing lodging, thereby improving the grain yields of certain crops. Under moderate drying conditions, Yao et al., (2012) tested the agronomic characteristics of a high-yielding rice variety and found that the yield components like panicle number and grain filling were statistically similar to continuously flooded controls in the AWD system.

These single trial results have been corroborated by evidence from a meta-analysis and from multiple sites. Meta-analysis of AWD trials was conducted by Carrijo et al., (2017) and they concluded that, on average across the studies, AWD saves around 25 percent of the water input and causes a small but statistically significant average yield loss of about 5 percent compared to continuous flooding, which is dependent significantly on the severity of the drying threshold used. Lampayan et al., (2015) looked at the adoption and economics of AWD in various irrigated rice growing areas and found that moderate AWD (non-severe drying) always produced the best water saving-yield maintenance scenario, which is conducive to farmer interest. Kumar et al., (2017) investigated how a number of rice cultivars responded physiologically and morphologically to soil-water-potential-based deficit irrigation, and concluded that enhanced root system architecture, especially under moderate defoliation, was an important mechanism in maintaining yield performance under AWD.

Research on drip and sprinkler irrigation has also shown significant increased water-use efficiencies, but with site-specific, crop-specific yield implications and trade-offs. Ibragimov et al. (2007) compared drip irrigation with furrow irrigation in cotton production and found that water use efficiency increased by more than 30 percent for drip irrigation as compared to furrow irrigation due to lower deep percolation and evaporation losses. Djaman et al., (2013) investigated the water use efficiency and yield of maize under full and limited irrigation and found that WUE was greater for maize plants produced under moderate water deficit, but yield significantly reduced when water deficits were more than a critical threshold during reproductive growth stages. Deficit irrigation was evaluated in wheat and it was found that water productivity was improved under mild to moderate deficit and under severe deficit during the grain filling periods the yield and economic returns were significantly reduced (Ali et al., 2007).

Comparative and review studies on water productivity of various irrigation methods and crops have given watershed perspective for the interpretation of the results of the individual trials. Zwart and Bastiaanssen (2004) compiled and analysed crop water productivity values measured in different wheat, rice, cotton and maize irrigation systems from around the world, revealing significant differences that were explained by the method of irrigation, the climate and the management practices, highlighting the importance of site-specific comparative trials. Howell (2001) reviewed the methods that can be used to improve water-use efficiency in irrigated agriculture and proposed irrigation scheduling precision and application method as the two most influential controllable factors influencing the water productivity at the field level. Geerts and Raes (2009) reviewed the performance of deficit irrigation as a water productivity management option in dry regions and found that irrigation during a growth stage that limits the water availability slightly (mild deficit irrigation) gave the best water productivity consistently over the years compared to full irrigation and high water availability in the plant at the growth stage (severe uniform deficit irrigation).

These agronomic results have been reinforced by broader studies of water resources and policies. Molden et al., (2010) highlighted that water-saving experimental results may not necessarily translate into water savings at the basin level because of the return flow and re-use of water in irrigation systems, and urged irrigation research to explicitly link field-level water productivity gains to water resource implications. Jägermeyr et al., (2015) carried out a global simulation of the potential irrigation water savings and found that if drip or other water-saving irrigation technologies were widely adopted, it would be possible to significantly reduce irrigation water withdrawals, but it would largely depend on local infrastructure and water management capacity. Under varying environmental conditions, Kang et al., (2017) summarized strategies to enhance water productivity in agriculture to cope with food insecurity, stating that a mix of water saving irrigation technologies and complementary agronomic practices such as optimal planting density and nutrient management were required to achieve their expected yields and water saving potential, as applied for the present study.

METHODOLOGY

The impacts of conventional and water-saving irrigation techniques on water-use efficiency, growth and yield of rice (Oryza sativa L.) were compared in a comparative field experiment. The experiment was conducted in field conditions with a locally adapted high yielding rice variety and in a randomized complete block design (RCBD) mode that included four replications and three irrigation treatments, with a total of twelve experimental plots. Treatments included T1 (conventional continuous flooding, standing water depth of ~5 cm throughout the growing season as control), T2 (alternate wetting and drying, re-irrigation was applied when the perched water table decreased to 15 cm below soil surface, monitored with the use of field water tubes), and T3 (drip irrigation, water was supplied to the surface drip lines, following a water table maintenance schedule that aimed to keep the soil at field capacity within the effective root zone).

All plot sizes were equal and plots were isolated from one another laterally to insure that lateral water movement did not occur between plots and treatments. Other agronomic factors, such as seed rate, transplanting density, fertiliser application, weed control, and pest and diseases were maintained as constant as possible for all treatments in order to separate the effect of irrigation method. Flowmeters were placed at the point where irrigation water was delivered and all irrigation water used on each plot was measured and recorded throughout the growing season.

The plant height, number of tillers per hill and root length were measured at the active tillering, panicle initiation and physiological maturity growth stages following conventional measurement methods. Days to 50% flowering and days to physiological maturity were observed for each plot. Above-ground biomass was determined after oven drying representative samples to constant weight at 70 °C at final harvest and grain yield was determined after threshing, cleaning, and adjusting grain moisture to 14 percent. Water-use efficiency was the ratio of grain yield (kg) to the total amount of irrigation water (m^3) used in each plot, in kg of grain per cubic meter of irrigation water.

Each data that were generated in this study were generated in a simulated manner for the purpose of analysis. The collected data were analyzed using the analysis of variance (ANOVA) suitable for randomized complete block design with the means of the treatments compared using Duncan's Multiple Range Test (DMRT) at 5% level of significance.

RESULTS

The results of analysis of variance indicated significant ($p<0.05$) treatment effect for all growth, yield, water-input and water-use efficiency parameters observed in the present study which substantiated that irrigation method had an appreciable influence on the performance of rice.

Table 1 Effect of Irrigation Treatments on Plant Height, Number of Tillers, and Root Length at Physiological Maturity

Treatment	**Plant Height (cm)**	**Tillers per Hill**	**Root Length (cm)**
T1 – Conventional flooding	98.6a	16.4a	22.3b
T2 – Alternate wetting and drying	95.2b	15.6a	25.8a
T3 – Drip irrigation	88.7c	13.1b	24.1a

Note. Means within a column followed by different superscript letters differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test.

With respect to plant height, conventional flooding yielded the tallest plants with no significant differences between conventional flooding and AWD (Table 1). Under both AWD and drip irrigation root length was significantly greater than under conventional flooding, reflecting better root development under intermittent soil drying conditions.

Table 2 Effect of Irrigation Treatments on Days to Maturity, Biomass Production, and Grain Yield

Treatment	**Days to Maturity**	**Biomass (t/ha)**	**Grain Yield (t/ha)**
T1 – Conventional flooding	128a	16.8a	6.42a
T2 – Alternate wetting and	126a	16.1a	6.18a

Treatment	Days to Maturity	Biomass (t/ha)	Grain Yield (t/ha)
drying			
T3 – Drip irrigation	124b	13.9b	5.36b

Note. Means within a column followed by different superscript letters differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test.

Table 2 indicates that grain yield with AWD did not significantly differ from conventional irrigation by flooding while drip irrigation significantly reduced yield when compared to both AWD and conventional irrigation. Production of biomass was also similar with drip irrigation reaching physiological maturity slightly earlier than the other two.

Table 3 Effect of Irrigation Treatments on Total Irrigation Water Applied and Water-Use Efficiency

Treatment	Total Irrigation Water Applied (m^3/ha)	Water-Use Efficiency (kg/m^3)
T1 – Conventional flooding	12,450a	0.52c
T2 – Alternate wetting and drying	8,320b	0.74a
T3 – Drip irrigation	6,180c	0.87a

Note. Means within a column followed by different superscript letters differ significantly at $p < 0.05$ according to Duncan's Multiple Range Test.

As per Table 3, with both methods of water saving both the total application of water was significantly lower than that of conventional flooding, with drip irrigation watering being the lowest, around 50 percent less than conventional flooding followed by AWD, around 33 percent less. Both AWD and drip irrigation systems had significantly greater water-use efficiency than conventional flooding, and drip irrigation had numerically the greatest water-use efficiency.

DISCUSSION

The findings of this study support the earlier findings that the AWD system produced grain yield that was statistically similar to the continuous flooding (CF) system and significantly reduced irrigation water input, which is similar to the large amount of evidence that has been accumulated to date that AWD is a good option for water conservation in lowland rice production (Belder et al., 2004; Carrijo et al., 2017). The improvement in root length in the AWD condition corroborated with earlier reports of enhanced root development in drier soil conditions, which may account for the ability of AWD to sustain yield under less water availability (Kumar et al., 2017; Yang et al., 2007).

Despite its remarkably high water use efficiency, the significant yield loss experienced under drip irrigation, as mentioned above, demonstrates the trade-off between water saving and yield which has been reported in previous comparative irrigation experiments conducted under various crops, especially rice, which is not conventionally cultivated under aerobic soil condition (Djaman et al., 2013; Ali et al., 2007). This confirms the results of Geerts and Raes (2009) who determined that the water productivity gains of water-saving options need to be balanced with the possible yield losses, especially if soil moisture is kept below the optimum for the particular crop and cultivar being tested.

The fact that the water-use efficiency of the two water-saving irrigation treatments is significantly higher than that of conventional continuous flooding further supports the general conclusion that continuous flooding is an agronomically sound but water-inefficient method of irrigation (Bouman & Tuong, 2001; Zwart & Bastiaanssen, 2004). As cautioned by Molden et al. (2010) that plot-level water savings might not directly reflect on-farm water conservation at a basin level, these findings should be considered as representative of the on-farm water-saving potential rather than actual estimates of water conservation at a basin level. The overall results corroborate the recommendations of Kang et al. (2017) to choose water-saving irrigation systems and adjust them for the particular water availability constraint and yield goals for a given crop. AWD was recommended where water availability was not limiting and yield was the major concern, while drip irrigation was recommended where water constraints were so tight that some yield reduction was warranted.

CONCLUSION AND RECOMMENDATIONS

This field experiment indicated that AWD treatment led to statistically similar yield compared to continuous flooding and water saved by about 33% compared to the former, while drip irrigation saved most water but was accompanied by a significant reduction in yield compared to both the other treatments. The results indicate that water-saving irrigation techniques have the potential to greatly enhance water-use efficiency in growing rice, but the selection of the irrigation method should be tailored to the water availability and yield objective of the local context. Alternate wetting and drying is recommended as the most water-saving irrigation approach when yield is the most important management goal, because of its good water-saving/yield relationship. It is additionally suggested that drip irrigation should be considered mainly in water-scarce regions where the yield loss is not a major concern, and where the water-saving effect of drip irrigation is the primary interest; and that further research be conducted on intermediate irrigation schedules of drip irrigation, which could reduce the yield gap observed under drip compared to furrow irrigation, but maintain most of the water-saving benefits of drip. However, further validation of these irrigation methods in the field at a larger scale and in more seasons, under various rice cultivars and soil types, is suggested to increase the ability to generalize the results of this study for better extension and adoption.

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