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Water productivity, yield and quality of aerobic rice (*Oryza sativa*) under drip-fertigation in comparison with puddled-flooded rice in semi-arid India

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Abstract
Increased water scarcity coupled with escalating pumping costs compels the farmers in India to opt for alternate production systems to flooded rice. Aerobic rice cultivation saves water but with yield penalty. Drip-fertigation (DF) has been proved to improve the crop, land, water and nutrient productivity in Agriculture. A field experiment was conducted at Warangal, Telangana State, India during 2011 and 2012 on a sandy loam soil to evaluate the performance and water productivity (WP) of aerobic rice with drip and N fertigation (120 kg ha^{-1}) at three schedules i.e., 100% pan evaporation (PE) (DF100), 150% PE (DF150) and 200% PE (DF200) in comparison with puddled-flooded (PF) system, aerobic-rainfed (AR), aerobic with surface irrigation (ASI) at 1.5 IW/CPE ratio, all replicated four times. The results revealed that PF rice maintained superiority in growth parameters, yield components and yield (5.06 t ha^{-1}) over aerobic rice. Grain yield was reduced by 45.8% in ASI rice mainly due to reduction (49%) in the filled spikelets per panicle compared to PF system. This yield gap was narrowed down to 15.2% in DF200 due to increased panicle production and filled spikelets attributed to consistently higher soil moisture between field capacity and saturation prevailed in DF200 which varied widely in ASI method. WP was doubled in DF200 with a water saving of 57% compared to PF rice while it was enhanced by 61% in ASI rice with 66% water saving. Physical quality parameters of rice did not differ due to flooded or aerobic cultivation.

Keywords: Aerobic rice, drip-fertigation, puddled-flooded rice, quality, root volume, water productivity, yield

Introduction
Worldwide, agriculture both contributes to and is threatened by climate change. It accounts for 13.5% of global greenhouse gas (GHG) emissions, or about 1.8 Gt carbon equivalent year^{-1} or 6.6 Gt of CO_2 equivalent year^{-1}, mainly in the form of methane (CH_4), and nitrous oxide (Swaminathan and Kesavan 2012)[43]. The greatest adverse impact of global warming related to climate change and sea level rise will be on the ecological foundations of agriculture broadly encompassing livelihoods, water security and food production systems. Changing climate has significant impacts on the availability of water, as well as quality and quantity of available and accessible water. In India, about 83% of available water is used for agriculture alone (Pathak *et al*. 2014)[30]. Rice is the single largest water consuming crop with lowest water productivity (Barker *et al*. 1998). Further, rice cultivation in puddled fields makes a large contribution to the release of GHGs like methane (Swaminathan and Kesavan 2012)[43]. The adoption of a system of rice cultivation that does not require huge amounts of water and chemical fertilizers with a proven record of much higher yields would be an effective solution. System of Rice Intensification (SRI) method holds promise for most of the cultivated varieties in small and marginal farmers' fields in South India (Adusumilli and BhagyaLaxmi 2011) [1]. Of late, many other water saving methods of rice cultivation like alternate wetting and drying, saturation culture, drum seeding and direct seeding are in vogue. These technologies increase the productivity of water inputs (rainfall, irrigation) mainly by reducing unproductive seepage and percolation losses and to a lesser extent by reducing evaporation (Sharma *et al*. 2015)[37]. Aerobic rice technology developed by International Rice Research Institute (IRRI) also caught the interest of the researchers wherein the crop is established in non-puddled, non-flooded

Fields and rice is grown like an upland crop with adequate inputs and supplementary irrigation when rainfall is insufficient (Bouman and Tuong 2001; Rajendra Prasad 2011) [4, 33].

Aerobic rice cultivation saves water input up to 50-60% (Sharma *et al*. 2015) [37] and increases water productivity by reducing water use during land preparation and limiting seepage, percolation and evaporation (Peng *et al*. 2012) [32]. It also reduces labour requirement and greenhouse gaseous emission from rice field. Even though water productivity is improved, many studies have revealed a yield penalty of rice from 30 to 70% under aerobic cultivation (George *et al*. 2002; Belder *et al*. 2005; Peng *et al*. 2006; Mallareddy and Padmaja 2013) [13, 3, 31, 24]. This yield gap is the major bottleneck hindering the farmers to adopt the aerobic cultivation. The shift from puddled to aerobic soil conditions brings profound changes in soil water status, aeration, soil organic matter turnover, nutrient dynamics, carbon impounding, weed flora and greenhouse gas emissions (Farooq *et al*. 2009; Rajendra Prasad 2011) [33].

To make aerobic rice successful, new varieties and management practices need to be developed. Optimum irrigation scheduling and nitrogen nutrition is critical for profitable yield realization of irrigated rice ecosystems (Maheswari *et al.* 2008) [23]. Drip irrigation is one of the advanced irrigation methods and apply required amount of water directly in the root zone at frequent intervals which may save sufficient quantity of water as compared to surface method of irrigation and improve the water productivity. Fertigation i.e., application of fertilizers and chemicals along with irrigation water aims at providing optimum nutrients required for the crop to get better and high quality produce (Kumar *et al*. 2014) [21]. It enables the application of soluble fertilizers and other chemicals along with irrigation water in the vicinity of the root zone. The application of water and nutrients in small doses at frequent intervals to the crop root zone ensures nutrients availability to the plants at the time of plants need. Drip irrigation and fertigation methods have been proved to be the water and nutrient efficient methods, respectively in agricultural and horticultural crops apart from increasing the crop productivity. Realising this fact, many State Governments in India are providing huge subsidies to farmers for drip irrigation systems. Aerobic rice with micro irrigation practices might lead to sustainable rice production for immediate future to address water scarcity with more benefits and environmental safety in the scenario of global warming by reduced methane emission as an added advantage (Parthasarathi *et al*. 2012) [29]. Studies on micro irrigation methods and fertigation in rice are lacking. Therefore, an attempt was made to evaluate the performance of aerobic rice under drip fertigation in comparison with puddled-flooded rice.

Materials and Methods

The field experiment was conducted during the rainy seasons of 2011 and 2012 at Regional Agricultural Research Station, Warangal ($18^0$00'53.2" N, $79^0$36'17.2" E and 275 m above mean sea level), Telangana State, India. Climate of the study site is sub-tropical and semi-arid type with mean annual rainfall of 885 mm and a mean annual evaporation of 1621 mm. Soil of the experimental field was sandy loam in texture with pH 7.9, electric conductivity 0.17 dS m^{-1}, 0.40% organic C (Walkley and Black 1934), 227 kg ha^{-1} alkaline $KMnO_4$oxidizable N (Subbiah and Asija 1956) [41], 11 kg ha^{-1} Olsen-P and 65 kg ha^{-1} ammonium acetate extractable-K. The soil had a bulk density of 1.64 and 1.73 Mg m^{-3} in 0-15 and 15-30 cm depths, respectively while the field capacity (FC) values for the corresponding depths were 15.6 and 15.8%, respectively. Rainfall, sunshine hours, maximum and minimum temperatures and daily evaporation from class A open pan evaporimeter were measured at meteorological observatory in the research station located at about 200 m away from the experimental site.

Six treatments consisting of crop establishment plus irrigation methods viz. puddled-flooded rice (PF), aerobic-rainfed rice (AR), aerobic rice with surface (flash) irrigation at 1.5 Irrigation water/Cumulative pan evaporation (IW/CPE) ratio (ASI), aerobic rice with N fertigation at 100% pan evaporation (PE) (DF 100), aerobic rice with N fertigation at 150% PE (DF 150) and aerobic rice with N fertigation at 200% PE (DF 200), were tested in a randomized block design replicated four times. The cultivar used for the study was 'WGL 20471' (Erramallelu) with medium duration (120 days), fine grain, drought tolerant and good cooking quality with a yield potential of 5.0 to 5.5 t ha^{-1}.

In the flooded field, land preparation consisted of wet tillage and puddling in standing water. Thirty days old seedlings from raised bed nurseries sown on the same day of aerobic rice, were transplanted with two seedlings per hill at a spacing of 30cm x 7cm. The field had always standing water from transplanting until about one week before physiological maturity, with water depth of 2cm at transplanting to 5 cm at panicle initiation stage. Irrigation outlets were fitted with 15 cm diameter PVC pipes that served as delivery channel of water for flooded and aerobic fields. Weeds could be controlled by the application of pre-emergence application of oxadiargyl at 0.1 kg ha^{-1} followed by bispyribac sodium at 0.2 L ha^{-1} and hand weeding at 25 and40 days after transplanting (DAT), respectively.

In aerobic method of cultivation, the field was dry-ploughed and harrowed but not puddled during land preparation. Seed at 40 kg ha^{-1} were sown in solid rows at a spacing of 30 cm between the rows in favorable soil moisture condition for germination. The experimental area for each plot both for aerobic and puddled condition was kept constant at 57.6 m^2. The row spacing was adjusted in aerobic method in accordance with the drip lateral spacing but sown in solid rows. Sowing was done on the same day both in aerobic and flooded rice i.e., 7th July and 27th June, during 2010 and 2011, respectively. Thinning and gap filling was done at 10 days after sowing. Weeds were controlled by pre-emergence application of pendimethalin at 1.2 kg a.i ha^{-1} followed by pyrazosufuron ethyl at 0.03 kg a.i ha^{-1} at 20 days after sowing (DAS). To control yellow mite, dicofol at 1.5 kg ha^{-1} was sprayed at 50 DAS and to control blast, tricyclozole at 0.3 kg ha^{-1} was sprayed at 90 DAS. To correct the 'Fe' deficiency which occurred at 20-30 DAS, ferrous sulphate was sprayed at 2.5 kg ha^{-1} for three times at weekly interval.

Drip irrigation was given to aerobic rice as per the schedules based on the evaporation from open pan evaporimeter (USWB class A) situated at Regional Agricultural Research Station, Warangal. The laterals of 16 mm diameter were laid out at 60 cm apart with a spacing of 50 cm distance between two inline emitters. The emitter discharge was 4.0 L hr^{-1} and application rate was 13.33 mm hr^{-1}. Control valves were fixed in all the plots to facilitate controlling the water flow as per the treatments. The drip system was operated on every alternate day till the quantity of water applied was equal to that evaporated in open pan evaporimeter (PE) in DF 100, 150% in DF 150 and 200% in DF 200. During rainy days, the quantity of water applied to each treatment was adjusted for the rainfall received. Buffer channels were constructed and sufficient land area was left in between the different treatments to avoid the seepage and percolation from one treatment to another. The quantity of water applied in each treatment was measured with a water meter fitted to the system. Effective rainfall was computed by water balance sheet method (Dastane 1985) [7].

A common dose of recommended nitrogen @ 120 kg ha^{-1} was applied for all the treatments in the form of urea. It was applied in fertigation treatments through ventury fitted to the drip system. The entire dose was split into ten equal parts and applied through drip at ten days interval starting from one days after sowing. It was applied in three splits (½ as basal, ¼ at maximum tillering stage and ¼ at panicle initiation stage) in AR, ASI and PF treatments. A recommended dose of 60 kg P_2O_5 and 50 kg K_2O ha^{-1} was applied uniformly to all the plots as basal in the form of single super phosphate and muriate of potash, respectively. All the other recommended cultural practices for achieving maximum grain yield were followed.

Plant samples were collected from 0.50 m^2 area at 30, 60, 90 days after sowing (DAS) and at maturity both in flooded and aerobic treatments for recording leaf area index (LAI), tiller number and above ground total biomass accumulation. However, LAI and tiller number in PF rice were recorded from 60 DAS onwards. Plant height and SPAD meter reading were recorded from the five randomly selected and tagged plants in the net plot area. A chlorophyll meter [SPAD-502, Soil and Plant analysis development (SPAD), Minolta Camera Co. Osaka, Japan] was used for chlorophyll measurement on ten top fully expanded leaves per plot at 30, 60 and 90 DAS and three SPAD readings (dimensionless values, 650/940 nm wave lengths transmittance ratio) were taken around the midpoint of each leaf blade, 30 mm apart from one side of the midrib. LAI was measured with LI-3100 area meter (LICOR, Lincoln, NE) for all samples. For recording the root parameters, five plants were randomly selected from each plot at 50% flowering stage. Root samples were collected by removing soil to depth of 45 cm along with the plants. A uniform soil volume of about 4500 cm^3 was excavated to collect root samples from all the treatments. Roots were carefully washed and root volume (cc $hill^{-1}$) was measured using the water displacement method as described by Misra and Ahmed (1987) [26]. The roots after recording the volume were kept in hot air oven at 60 ºC till the constant weight was obtained and expressed as g $hill^{-1}$. Soil moisture content was estimated in 0-15 and 15-30 cm depth at weekly interval during the entire crop growth period and after the incident rainfall with the help of soil moisture meter profile probe (PR-2) which was calibrated with gravimetric method at the beginning of the experiment. Plants from one square meter area were sampled at maturity to determine the aboveground biomass and the yield components. Number of panicles for each hill within 1.0 m^2 area was counted. Plants were separated into straw and panicles. After recording their length, panicles were hand threshed and illfilled spikelets were separated from filled ones by submerging them in tap water. Sterility of spikelets (%) and thousand grain weight of filled spikelets was determined. Grain and straw yield was determined from a net plot area of 40.3 m^2 leaving boarder rows and adding the grain and straw weight obtained from one square meter area removed for recording yield components, respectively. The grain yield was adjusted to 14% moisture content and straw dry weight was determined after oven drying at 70 ºC to constant weight. Harvest index was calculated as 100x filled spikelet weight/above ground total biomass. N concentration of grain and straw was separately determined by using microkjeldahl digestion method and expressed in kilograms of N per ha in grain and straw, respectively. Water productivity (WP) was calculated as grain yield per total water received from rainfall and irrigation and expressed as: WP = Y/R+I (kg grain kg^{-1} of water) where, R is the amount of effective rainfall (mm) and I is the amount of irrigation water applied (mm). Agronomic Nitrogen-use efficiency (ANUE) (kg grain kg^{-1} applied N) was calculated using the equation: NUE = Y/N; where Y is the grain yield (kg ha^{-1}) and N is the quantity of N applied (kg). For recording the grain physical quality parameters, a sample of one hundred grams of well dried paddy (14% moisture) from each treatment was dehulled in standard “Satake” dehuller and the weight of brown rice was recorded. It was subjected to milling for 90 sec *i.e.,* 5 per cent milling in “Satake” polisher (Type-TM 05) and the weight of polished rice was recorded. The polished kernels were passed repeatedly through a rice grader having 5 mm grooves to separate the brokens from the head rice kernels. Full rice and a length of three-fourth kernels were taken as whole polished rice for computation. Hulling, milling and head rice recovery percentage was computed. All the data on growth and root parameters, yield components, yield, N uptake, WP and ANUE were analysed with INDOSTAT for windows (version 8.0) for one-way ANOVA, keeping the years as the main and irrigation treatments as sub-effects using split-plot design. The treatment means were separated using least significant differences (LSD) at 5% level of significance.

Results and discussion

Weather

The weekly mean maximum temperature during crop growth period ranged from 27.1 to 33.0 ºC and 26.1 to 30.6 ºC during 2011 and 2012, respectively. The weekly mean minimum temperature for the corresponding period ranged from 22.3 to 26.1 ºC and 20.0 to 26.0 ºC, respectively, while the average maximum and minimum temperatures during the same period were 30.5and 24.0 ºC during 2011, and 28.7 and 23.3 ºC during 2012, respectively. The weekly mean relative humidity (RH) ranged from 60.1 to 81.1% during 2011 and 74.6 to 80.3% during 2012, while the average relative humidity was 72.7 and 76.9%, during 2011 and 2012, respectively. A total rainfall of 349.2 and 784.0 mm was received on 26 and 53 rainy days during the crop growth period in 2011 and 2012, respectively. Thus, in the first year, the rainfall was about 30% less than the decennial average rainfall of the site, but in the second year, it was 125% higher than that received during first year (Fig. 1). The total evaporation during the growing season of rice was 379 and 387.9 mm during 2011 and 2012, respectively. The weekly mean bright sunshine hours per day varied from 1.5 to 7.0 hours and 0.7 to 9.2 hours during 2011 and 2012, respectively.

Differences in experimental factors

Table 1 & 1a shows computed *F* values for the differences in grain yield, yield components, growth, root parameters and N uptake of rice between/among years and crop establishment plus irrigation treatments. All the measurements showed significant difference (P=0.05) among the irrigation treatments. Variations due to years were also significant except for panicle length, filled spikelets and harvest index. The interaction between year and treatments was significant for few parameters i.e., root dry weight, spikelet sterility and straw yield.

Soil moisture dynamics

Data on soil moisture (%) (SM) recorded at weekly intervals throughout the rice growth period is presented in Fig. 2 and 3. It was observed that during 2011, in DF200 and DF150, higher SM levels (FC and above) were maintained throughout the crop growth at 0-15 and 15-30 cm depth (Fig. 2). In DF100 plots also, SM was maintained above FC but it was below the level observed in DF150 and DF200 in the top layer. But after ceasing of rains (12WAS) which coincided with pre-flowering stage, soil moisture in DF100 was below the FC. In ASI plots, SM was deviating widely touching FC level during rainfall and irrigation events up to 11WAS, after which it was maintained consistently at lower levels. The rainfed plots (AR) had the lowest levels of SM far below the FC throughout the crop growth period at both the depths except during the rainfall events. During 2012, SM remained almost same in all the treatments up to 10 WAS (Fig. 3). It is attributed to well distributed and higher rainfall. Later on, in DF plots, it was maintained at higher levels than FC which coincided with the flowering period but in ASI and AR plots, substantial reduction in the level of moisture during 12, 14 and 16 WAS much below the FC was noticed at both the depths of observation. Studies conducted by O'Toole and Garity (1984) [27] and Mahajan *et al*. (2012) [22] indicated the possibility of spikelet sterility in rice when soil moisture potential during flowering was higher than -10 kPa. It is also evident from the present study that dry soil conditions in AR and ASI resulted in increased spikelet sterility and reduced grain weight.

Crop growth and development

Temporal curves of growth parameters such as plant height, LAI, SPAD meter reading, tiller production and dry matter production up to 90 DAS depicted in Fig 4 to 8 indicated that crop establishment plus irrigation methods influenced the rice growth. During 2011, at 30 DAS, plant height in all the treatments was similar (Fig. 4). At later stages i.e., 60 and 90 DAS, the differences in plant height became wider with the advancement of the crop growth except among the DF treatments. By 90 DAS, among all the treatments, the crop grew taller in PF rice followed by DF200, DF150, DF100 and ASI. In AR, the incremental advance in plant height was low. However, during second year (2012), the differences in plant height in various treatments were less pronounced which might be attributed to high and well distributed rainfall during vegetative growth period.

During 2011, DF200 registered higher LAI measured at 30, 60 and 90 DAS over DF100 but on a par with that of DF150 (Fig. 5). LAI in AR and ASI rice was equal to that of DF100 schedule at 30 DAS. At 60 DAS, ASI and PF rice were comparable to that of DF100 drip schedule but the leaf area development in AR rice was found to be reduced. At 90 DAS, PF rice had more LAI over all the treatments including the drip fertigation (DF100, DF150, DF 200). LAI was much lower in AR rice. Higher LAI under DF200 and DF150 compared to ASI and AR rice could be due to the prevalence of higher SM levels throughout growth period (Fig. 2 and 3) which might have maintained normal cell division, elongation and leaf expansion. Rice plants are very sensitive to water stress when exceeding critical levels of soil drying below saturation. Leaf expansion stops completely when root-zone soil water potential exceeds 50 kPa (Woperies *et al*. 1996) [45]. Maheswari*et al*. (2008) [23] and Mallareddy*et al*. (2013) [24] also observed increased LAI with increased frequency in irrigation. During 2012, the difference in LAI due to crop establishment plus irrigation schedules through drip system/surface flash irrigation was not significant at all the stages. It might be due to well distributed rainfall. Bouman*et al*. (2005) [5] from IRRI, Philippines also recorded more or less same LAI in flooded as well as aerobic condition during wet years. Data on SPAD values observed at 30, 60 and 90 DAS for two years is depicted in Fig.6. Although the SPAD value in AR rice tended to be lower than those in other treatments, the difference was not significant. It was the highest in PF rice among irrigation treatments for two years. Reddy *et al*. (2007) [34] also observed increased chlorophyll content in flooded condition compared to aerobic condition. The reduction in chlorophyll content under water stressed aerobic condition could be due to enhanced chlorophyllase enzyme activity which is deleterious to plant productivity (Sheela and Alexander 1996) [38].

During first year, tiller production in AR was very less compared to other treatments at all the stages (Fig. 7). However, in PF rice tillers were recorded only form 60 DAS onwards, as 30 DAS coincided with planting date. At this interval of observation, PF rice had less number of tillers compared to aerobic rice except in AR rice. It might be due to transplanting shock but tiller production picked up later. At 90 DAS, tiller number with PF rice was similar to DF rice at all the three schedules during both the years.

During 2011, AR rice had lower dry matter production at all the stages but irrigated aerobic rice at 1.5 IW/CPE ratio (ASI) was similar to drip irrigation schedule of DF100 (Fig. 8). PF rice was superior to all other treatments at 90 DAS. During 2012, AR and ASI rice were similar to drip irrigated treatments at 30 and 60 DAS but at 90 DAS, AR rice had a setback due to drought that prevailed from 98 DAS due to retreat of south west monsoon which coincided with 50% flowering. PF rice accumulated more dry matter at 90 DAS than other treatments. Observations of Maheswari *et al*. (2008) [23], Shekara *et al*. (2010) [39] and Mallareddy *et al*. (2013) [24] also indicate the strong relationship between dry matter production and soil moisture content in aerobic rice.

Data recorded at maturity on plant height, tillers and dry matter accumulation revealed that there was difference in rice growth during dry and wet years (Table 2). Taller plants with more tillers m^{-2} and dry matter accumulation were observed during 2012 compared to that of 2011 in all the treatments. This might be due to well distributed rainfall especially during vegetative growth period. Among the treatments, significantly taller plants were recorded in PF rice followed by DF200 and DF150. Shortest plants were observed in AR rice. In contrast to the plant height, maximum number of tillers was observed in DF200, DF150 and DF100 and the latter two treatments were similar to PF and ASI rice. Least number of tillers was produced in AR rice. The dry matter produced in DF200 and PF rice was similar and superior to the rest of the treatments. Further, DF150 was superior to DF100 and ASI rice which were at par with each other. Least dry matter was associated with AR rice irrespective of the season either wet or dry. Number of days taken to 50% flowering did not differ due to irrigation treatments during both the years.

Root parameters

Root volume and dry weight was recorded at 50% flowering stage. Data presented in Table 2 indicated that root volume was significantly higher during 2011 (dry year) over 2012 (wet year). Highest root volume was recorded in PF rice but similar with that of AR rice. Among the DF treatments, DF200 had highest root volume superior over DF100 but similar to DF 150 and the latter two were at par with each other as well, along with ASI rice. For root dry weight, the interaction between year and irrigation treatment was found to be significant (Table 4). Highest value of root dry weight was observed in AR rice during 2011 which was significantly superior to the rest of the treatments during both the years of experimentation. Except in PF rice, RDW was significantly higher during dry year over that in wet year in all the treatments. In 2011, PF rice and DF200 were similar while ASI, DF100 and DF150 had the same RDW. During wet year (2012), AR was at par with PF rice. RDW also did not vary between ASI, DF200 and DF100, DF150.

Yield components

Yield components such as panicles and 1000-grain weight differed between wet and dry years while panicle length and filled spikelet number per panicle were not influenced by the difference in weather conditions between the years (Table 2). The interaction effect between year and treatments was significant only for percentage of sterile spikelets (Table 4).

The average panicles m^{-2} varied from 340 in PF rice to 192 in AR rice. Significantly higher number of panicles was observed in PF rice over aerobic rice including DF treatments at all the three schedules. However, among the drip fertigation treatments, panicles m^{-2} in DF200 were significantly more than those in DF150 and DF100, and no significant difference was observed between DF150 and DF100. It is to be noted that, even though DF200 produced significantly more tillers, the panicle number was higher in PF rice. Apart from number, lengthier panicles were produced in DF200 next to PF rice followed by DF150. The panicle length in DF150, DF100 and ASI was similar and the latter two treatments were at par with AR rice.

The number of filled spikelets per panicle in PF rice and DF 200 were similar and DF200 was again at par with DF150 (Table 2). DF100 and ASI were similar with respect to filled spikelets and AR rice was the last in the sequence. Spikelet sterility was influenced by year x treatment interaction (Table 4). Highest percentage (42 during 2011) of sterile spikelets was found in AR rice during both the years. It was reduced in the order of ASI, PF, DF100, DF200 and DF150. Growing rice aerobically with surface (flash) irrigation (ASI) led to significant increase in sterility of spikelets but all DF three schedules were at par with PF rice. This implies that AR and ASI rice may have suffered water and N stress around panicle initiation to grain filling stage causing reduction in grain number. Analysis of rainfall pattern (Fig. 1) indicates that rains ceased after 11th WAS during 2011 and 14thweek during 2012 even though a little amount of rainfall occurred after a dry spell of 3 and 2 weeks, respectively. The dry spell occurred 25 days before 50% flowering in 2011 and coincided with 50% flowering in 2012 though it distributed well during vegetative stage. This fact might be responsible for the increased sterility of spikelets and less grain weight in AR and ASI compared to PF rice during both the years. Several researchers also indicated the effects of water stress at different stages i.e., anthesis stage (De Datta 1989) [8], flowering (Ekanayake *et al*. 1990) [10], pollen germination (Saini and Westgate 2000) [35], panicle exsertion (O'Toole and Namuco 1983) [26] and peduncle length (He *et al*. 2009) [15] finally leading to sterility of spikelets. Drought stress during late panicle development also sharply decreases the percentage of filled spikelets (Fageria 2001) [11]. Reduction in the spikelet sterility in DF plots in wet year might be due to the stable availability of moisture at higher levels (Fig. 3) and nitrogen in required quantities all throughout the crop growth period including the flowering stage. During 2011 (dry year), significant increase in spikelet sterility was observed in DF100 over DF150. This demonstrates that small differences in SM result in spikelet sterility and thereby the yield. Further, it is to be noted that the last split of N through fertigation in DF plots coincided with pre-flowering stage which possibly supplied the N during spikelet differentiation and development. Senanayake *et al*. (1996) [36] and Kobayasi *et al*. (2001) [20] reported that rice grain yield is mostly limited by the total number of fertile and sterile spikelets. Kamiji *et al*. (2011) [18] concluded that spikelet number is influenced mainly by a plant's N status at the late spikelet differentiation stage. Thus in the present study, the spikelet number increased in DF200 at par with PF rice which is attributed to optimal moisture and N supply at spikelet differentiation and filling stage. 1000-grain weight was similar in all the DF treatments and PF rice except AR rice in which lower grain weight was recorded.

Yield and N uptake

Grain yields strongly responded to the establishment combined with irrigation methods/regimes (Table 3). Significantly higher rice grain yield was obtained during wet year (2012) compared to dry year (2011) which was possibly better demonstrated by the production of higher dry matter and tillers due to well-distributed rainfall in 2012 during vegetative stage. Flooding of water (PF) in rice resulted in higher yields over aerobic rice across all the water management treatments in the latter one. It was consistent with the observed higher LAI values, dry matter production and increased N uptake. However, in aerobic rice, among the treatments, DF200 resulted in superior yields over the rest of the treatments and there was pronounced difference among other treatments as well. DF150 was again superior to DF100 and ASI in both of which rice yield was similar. In AR rice, the grain yield was substantially reduced. The mean yield reduction was in the order of 15.2, 32.2, 42.3, 45.8 and 81.4% in DF200, DF150, DF100, ASI and AR, respectively compared to PF rice.

Kadiyala *et al*. (2012) [17] opined that yield losses should be limited to a maximum of 15 to 20% when compared to the yields attained under traditional flooded method to make aerobic rice more adoptable by the farming community. The present study demonstrated the potential of drip fertigation in narrowing down the gap in yields between aerobic and flooded rice. Studies conducted by Kato *et al*. (2009) [19] in Japan also revealed 7.9 to 9.4 t ha^{-1} of yields under aerobic system with high-yielding varieties. This demonstrates the potential for achieving similar or even higher yield levels than that achieved under traditional flooded methods through high-yielding aerobic rice varieties and optimum cultural management.

Straw yield of rice varied due to year x treatment effect (Table 4). During 2011, PF rice had highest straw yield but on par with DF200 while during 2012, the latter treatment registered significantly more straw yield than over all the other treatments including PF rice. Interestingly, straw yield in DF treatments was different between dry and wet years but remained the same in PF, AR and ASI rice. Harvest index did not vary between the years, but influenced by the treatments.

It was higher in PF rice but statistically at par with DF200. DF150 and DF100 were similar between themselves as well as DF200 and ASI. Least HI was found in AR rice. The low harvest index of aerobic rice in field experiments in China has been found to correlate with low percentage of filled grains (Bouman*et al*. 2006) [6]. Increase in harvest index indicates the capacity of the crop to divert more photosynthates to the sink even though similar dry matter is produced. In the present experiment it was noticed that filled spikelets in DF200 was similar to PF rice which resulted in better HI compared to ASI rice.

Nitrogen (N) uptake in grain and straw significantly differed between the years (Table 3). It was higher in 2012 than in 2011. Among the treatments, the highest N uptake by grain and straw was recorded in PF rice. It was 36 and 8% more than that of DF200 in grain and straw, respectively. The narrowed difference in straw N uptake might be due to the fact that the straw yields were similar between PF and DF200. N uptake in DF100 and ASI was similar both in grain and straw but inferior to that in DF150 while the lowest was recorded in AR rice. The lower N uptake in aerobic rice with surface flash irrigations with three splits of N application (ASI) compared to that in DF200 and DF150 might have been due to increased gaseous N losses under aerobic system coupled with the poor synchrony between crop needs and N availability (Belder *et al*. 2005) [3]. However, high N uptake in drip fertigation plots at the same rate of application might be due to application of water and nutrients in small doses at frequent intervals to the crop root zone which leads to nutrient availability in tune with the plant need.

Water-use and productivity

Total water (irrigation input and rainfall) in PF rice including land preparation and nursery raising was 1683.4 and 1452.8 mm during 2011 and 2012, respectively (Average figure was shown in the Table 3). Correspondingly, AR rice used only 221.5 and 256.9 mm, respectively. In other aerobic treatments i.e., ASI, DF100, DF150 and DF200, the average water used ranged from 401.8 to 674.0 mm. Growing rice in aerobic condition with flash irrigations (ASI) resulted in a water saving of 66% (64 and 68% in 2011 and 2012, respectively). Similarly, water saving of 76, 67 and 59% was observed in irrigation schedules of DF100, DF150 and DF200, respectively during first year (2011) over the traditional flooded method. During second year (2012), the water saving in the respective treatments was 73, 64 and 55%. Considerable water saving in aerobic method of cultivation over flooded method had been brought out by several researchers (Belder *et al*. 2005; Bouman *et al*. 2005; Kadiyala *et al*. 2012) [3, 5, 17].

Water productivity (WP) of rice significantly changed with years and treatments (Table 3). Compared to dry year (2011), WP was enhanced by 25% in wet year (2012). This might be due to high rainfall associated with improved yields in wet year and possibly favorable RH regimes prevailed during wet year. Among the treatments comprising flooded and aerobic condition, highest WP was recorded in DF100 followed by DF150 and DF200. ASI rice was the next best treatment. Interestingly, WP in flooded (PF) and AR rice was statistically similar. In general, DF rice registered higher WP compared to flash irrigated aerobic (ASI) and flooded (PF) rice. In DF100 and DF150, lower amounts of water were used compared to ASI but WP was significantly improved due to increased yields. WP was improved by 121, 109 and 94% in DF100, D150 and DF200, respectively over PF rice. He *et al*. (2016) also reported 2.5 times improvement in WUE with drip irrigation than in flooded rice with the similar yields. It could be due to more precise dosage and timing of irrigation water applied in relation to crop transpiration and soil water holding capacity (Doorenbos and Pruit 1984) [9]. Higher water productivity in aerobic system and drip irrigation compared to flooded rice was also reported by Shekara*et al*. (2010) [39]; Ghosh and Singh (2012) [14]; Sridharan and Vijayalakshmi (2012) [40].

Agronomic N-use efficiency (ANUE)

Similar to WP, ANUE was also higher during 2012 (wet) compared to 2011 (dry) due to higher grain yields obtained during wet year (Table 3). It was also found to be the highest in PF rice which was superior to aerobic rice at all the irrigation regimes i.e., AR, ASI, DF100, DF150, DF200 corresponding to the yield levels. On an average, ANUE in drip fertigation increased by 32 per cent compared to ASI rice. The results of the study conducted by Sui *et al.* (2013) at 7 different sites in China indicated that achieving synchrony between N supply and crop demand is the key to optimizing tradeoffs amongst yield, N efficiency and environmental protection in crop production for which fertigation may be the potential option. Improved N use efficiency in aerobic rice with increased water input was also reported by Mahajan *et al*. (2012) [22].

Grain physical quality parameters

Data on grain qualitative parameters like hulling, milling and head rice recovery percentage was collected for all the treatments. There was no significant difference among the treatments with respect to all the physical quality parameters irrespective of the wet or dry years (Data not shown).

Conclusion

Aerobic rice will remain the best option to flooded rice during failure of monsoon or periods of deficit rainfall in semi-arid India. Further, growing rice aerobically will have positive implications on ground water decline as shifting of paddy to groundwater in many states of India has precipitated a ground water crisis. Water saving and higher water productivity are the advantages of aerobic rice but the yield gap between flooded and aerobic systems should be narrowed down to make it an economically viable option. Our study demonstrated the potential of drip-fertigation for addressing the yield gap between flooded and aerobic rice apart from savings in water. Scheduling irrigations at 200% of the open pan evaporation with fertigation at 120 kg N ha^{-1} was found to be the best treatment with significant reduction in yield gap of 46% between flooded and aerobic systems to 15.2%. Water productivity was doubled with drip-fertigation which is the most crucial in rice in the water deficit scenario. Many states in India are supplying drip-fertigation systems at more subsidized rates which can also be extended to water exhaustive crops like rice.

Table 1: Analysis-of-variance of *F*-values of growth, root parameters and yield components between/among years and irrigation treatments

Source of variation	df	PHM	TM	DMM	D50%F	RV	RDW	PN	PL	FSPP	STPS	1000-GW
Year (Yr)	1	4.98*	8.20**	186.58***	NS	48.32***	89.35***	11.59**	NS	NS	NS	62.97***
Irrigation treatment (I)	5	8.02***	9.74***	45.47***	NS	22.17***	41.05***	14.94***	12.32***	43.87***	66.05***	11.05***
Yr X I	5	NS	NS	NS	NS	NS	3.98**	NS	NS	NS	2.58*	NS

Table 1a: Analysis-of-variance of *F*-values of yield, N uptake, WP, ANUE and grain quality parameters between/among years and irrigation treatments

Source of variation	df	GY	SY	HI	WP	ANUE	NUPG	NUPS	Hulling %	Milling %	HRR %
Year (Yr)	1	9.54**	28.20***	NS	22.83***	9.62**	7.39*	105.27***	NS	NS	NS
Irrigation treatment (I)	5	101.69***	34.39***	49.97***	34.69***	101.49***	107.69***	6.89***	NS	NS	NS
Yr X I	5	NS	3.29*	NS	NS	NS	NS	NS	NS	NS	NS

*Significant at the *P*=0.05 level
**Significant at the *P*=0.01 level
***Significant at the *P*=0.001 level
NS, not significant at the *P*=0.05 level

PHM-Plant height at maturity
TM-Tillers at maturity
DMM-Dry matter at maturity
D50%F-Days taken to 50% flowering
RV-Root volume
RDW-Root dry weight
PN-Panicle number
PL-Panicle length
FSPP- Fertile spikelets per panicle
STPS - Sterility percentage of spikelets
1000-GW-1000 grain weight
GY-Grain Yield
SY-Straw Yield
HI-Harvest Index
WP-Water Productivity
ANUE-Agronomic N Use Efficiency
NUPG-N uptake by grain
NUPS-N uptake by straw
HRR-Head Rice Recovery

Table 2: Growth, root parameters and yield components of rice subjected to various irrigation treatments

	Plant height at maturity (cm)	Tiller m^{-2} at maturity	Dry matter accumulation at maturity (kg ha^{-1})	Days taken to 50% flowering	Root volume at 50% flowering (cc hill^{-1})	Panicles m^{-2}	Panicle length (cm)	Filled spikelets per panicle	1000-grain weight (g)
Year									
2011	79.8 b	368.8 b	8056 b	95.5 a	27.72 a	250.8 b	22.90 a	159.1 a	16.87 b
2012	89.5 a	407.2 a	10093 a	95.9 a	23.77 b	265.2 a	22.87 a	159.0 a	17.54 a
Irrigation treatment									
PF	105.6 a	380.5 b	11992 a	95.5 a	33.44 a	339.5 a	26.95 a	233.5 a	18.54 a
AR	70.2 c	261.0 c	5172 d	97.6 a	31.49 a	192.0 d	19.75 d	72.0 d	16.08 c
ASI	80.7 bc	363.5 b	7393 c	95.8 a	21.59 c	236.0 c	21.60 cd	119.5 c	16.87 b
DF100	79.8 bc	421.9 ab	8114 c	95.7 a	19.93 c	234.5 c	21.78 cd	132.3 c	17.09 b
DF150	84.5 b	426.6 ab	9635 b	94.9 a	22.81 bc	249.4 c	23.14 bc	187.0 b	17.45 b
DF200	87.1 b	474.3 a	12138 a	95.1 a	25.21 b	296.6 b	24.11 b	210.1 ab	17.18 b

Different letters indicate statistical significance at the *P*=0.05 level within the same column
PF-Puddled-flooded
AR-Aerobic-rainfed
ASI-Aerobic-surface irrigated
DF100-Drip-fertigation at 100% pan evaporation (PE)
DF150-Drip-fertigation at 150% PE
DF200-Drip-fertigation at 200% PE

Table 3: Grain Yield, Harvest Index, N uptake, Water Use, WP and ANUE of rice subjected to various irrigation treatments

	Grain yield(t ha^{-1})	Harvest Index	N uptake by grain(kg ha^{-1})	N uptake by straw (kg ha^{-1})	*Total water use (mm)	WP (g grain kg^{-1} water)	Anue
Year							
2011	3.04 b	37.8 a	41.88 b	28.84 b	-	0.48 b	25.36b
2012	3.42 a	38.5 a	44.89 a	39.14 a	-	0.60 a	28.47a
Irrigation treatment							
PF	5.06 a	44.74 a	79.69 a	47.39 a	1568.1	0.33 d	42.17a
AR	0.94 e	21.83 d	9.55 e	21.26 e	239.2	0.39 d	7.83e
ASI	2.74 d	38.05 c	35.61 d	30.75 cd	535.5	0.53 c	22.80 d
DF100	2.92 d	40.75 bc	34.44 d	27.74 cd	401.8	0.73 a	24.35 d
DF150	3.43 c	41.25 bc	42.39 c	33.14 bc	536.3	0.69 b	28.58 c
DF200	4.29 b	42.25 ab	58.61 b	43.67 ab	674.0	0.64 b	35.78 b

*Average value of two years
Water use includes effective rainfall plus irrigation in aerobic rice treatments

Table 4: Interaction between year and irrigation treatment for root dry weight, sterility of spikelets and straw yield of rice

Year (Yr)	Irrigation treatment (I)					
	PF	**AR**	**ASI**	**DF100**	**DF150**	**DF200**
Root dry weight at 50% flowering (g hill^{-1})						
2011	12.03	14.35	10.10	8.38	9.30	11.25
2012	11.20	10.25	8.30	6.83	7.58	8.63
	SEm±	LSD (0.05)				
I at same Yr	0.40	1.16				
Yr at same or different I	0.40	1.25				
Sterility of spikelets (%)						
2011	14.60	42.20	20.00	15.43	9.43	10.85
2012	10.40	31.70	16.20	11.68	11.50	8.68
	SEm±	LSD (0.05)				
I at same Yr	1.79	5.16				
Yr at same or different I	2.13	7.58				
Straw yield (t ha^{-1})						
2011	6.27	3.02	4.05	3.87	4.65	5.86
2012	7.35	3.91	4.93	5.92	7.04	8.94
	SEm±	LSD (0.05)				
I at same Yr	0.36	1.03				
Yr at same or different I	0.40	1.37				

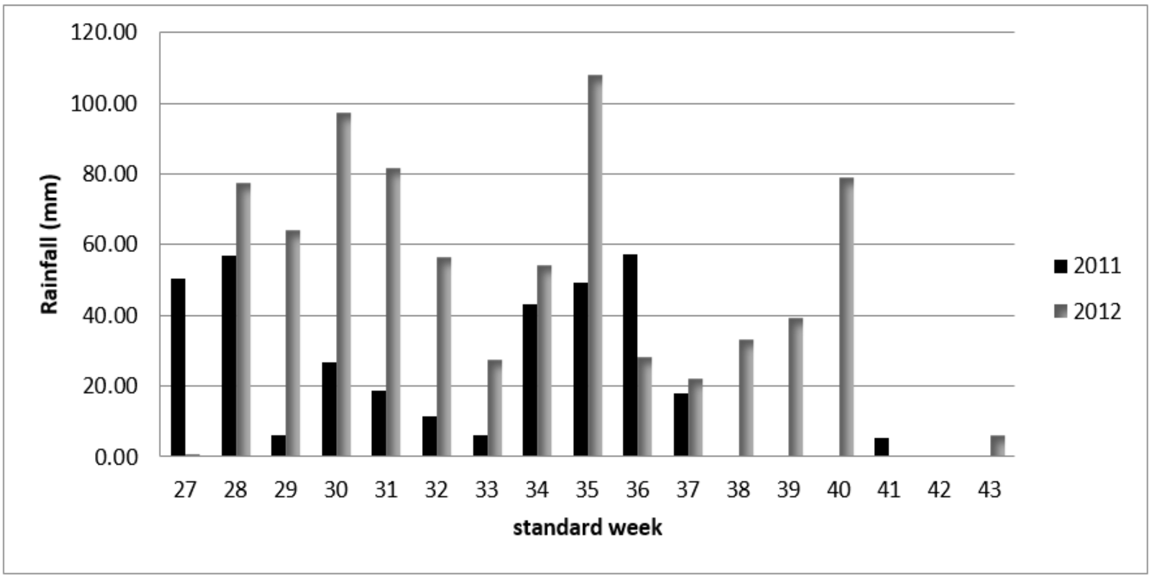
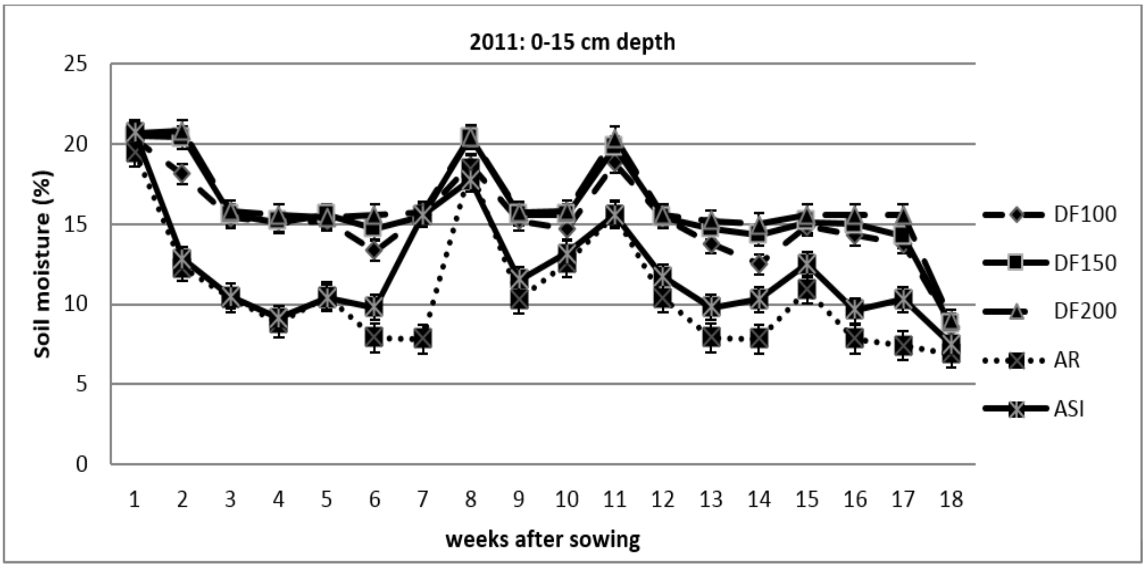


Fig 1: Rainfall distribution during growing season of rice in the experimental years



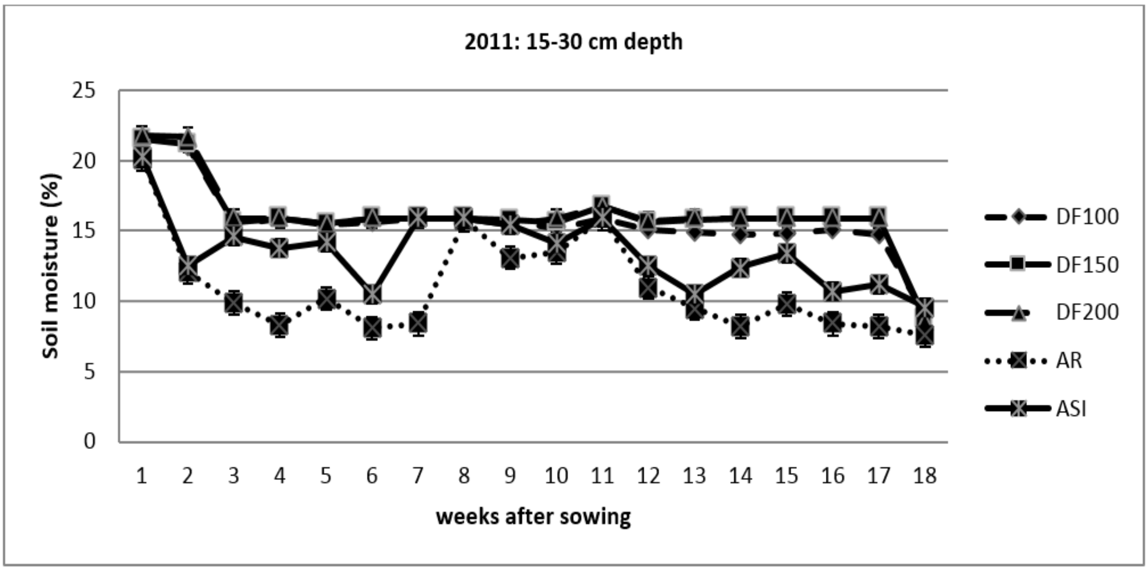
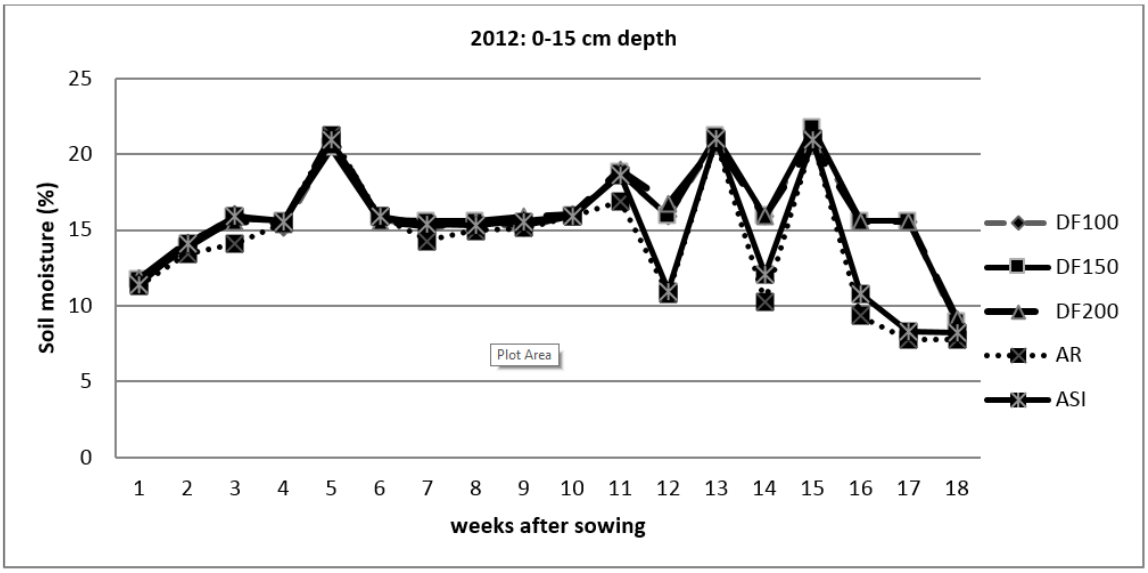


Fig 2: Soil moisture dynamics in different irrigation treatments at 0-15 and 15-30 cm depth in 2011



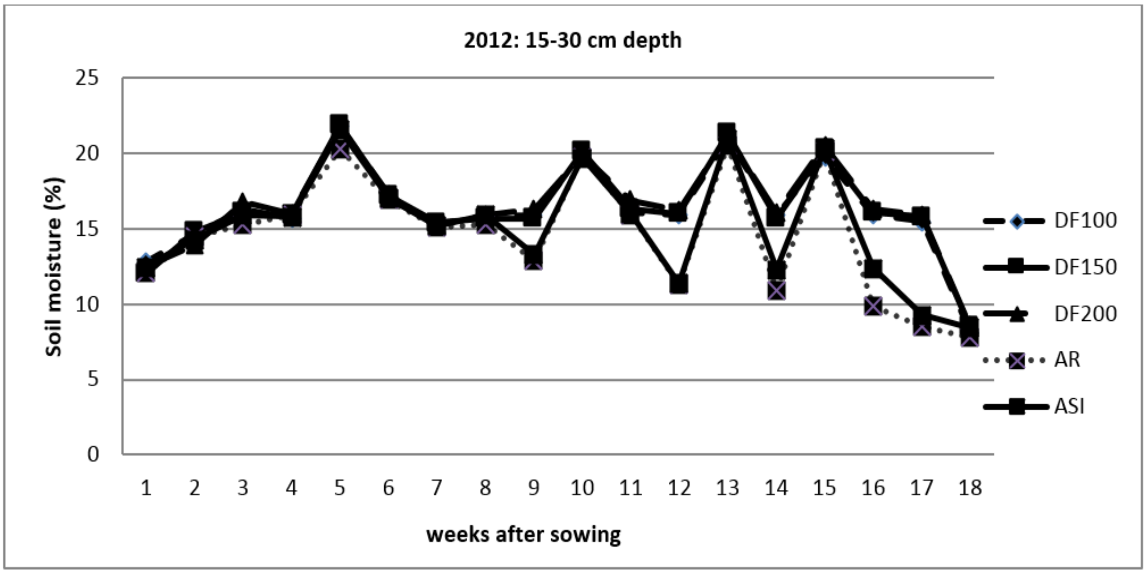


Fig 3: Soil moisture dynamics in different irrigation treatments at 0-15 and 15-30 cm depth in 2012

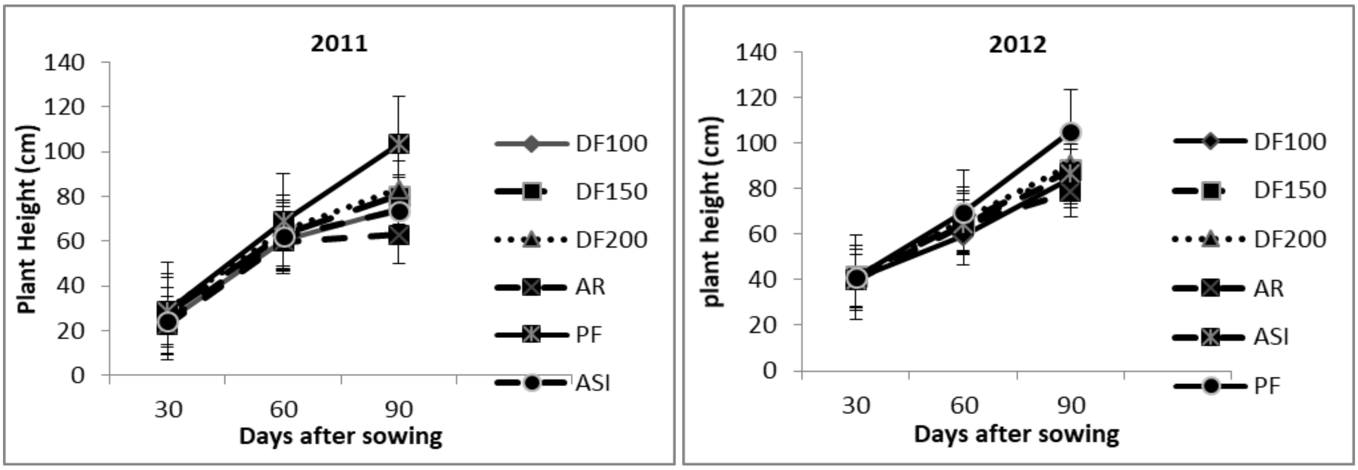


Fig 4: Plant height (cm) of rice under different irrigation treatments. Bars indicate the standard errors

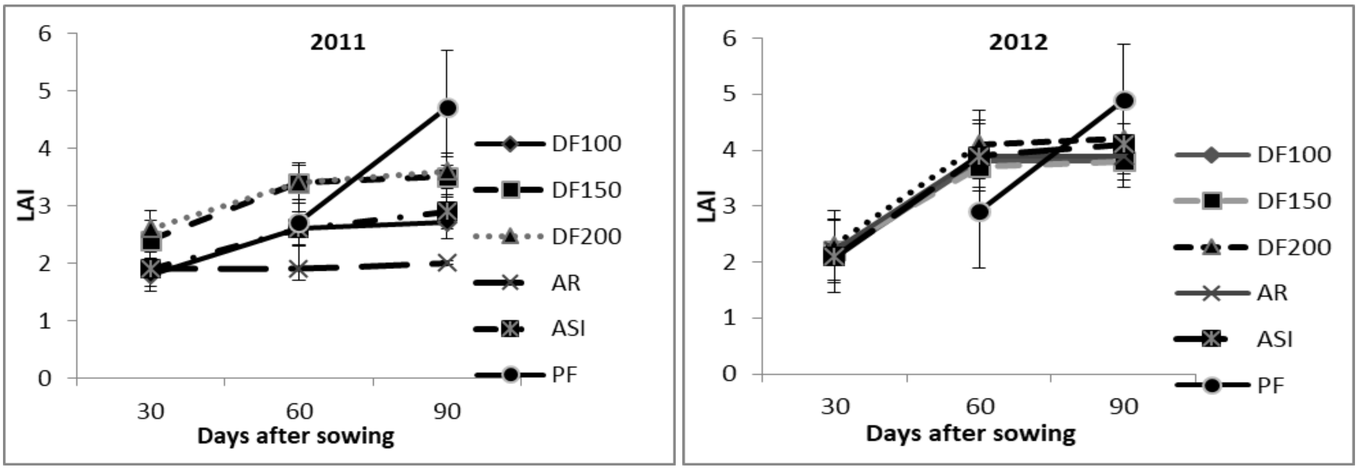


Fig 5: LAI of rice under different irrigation treatments. Bars indicate the standard errors

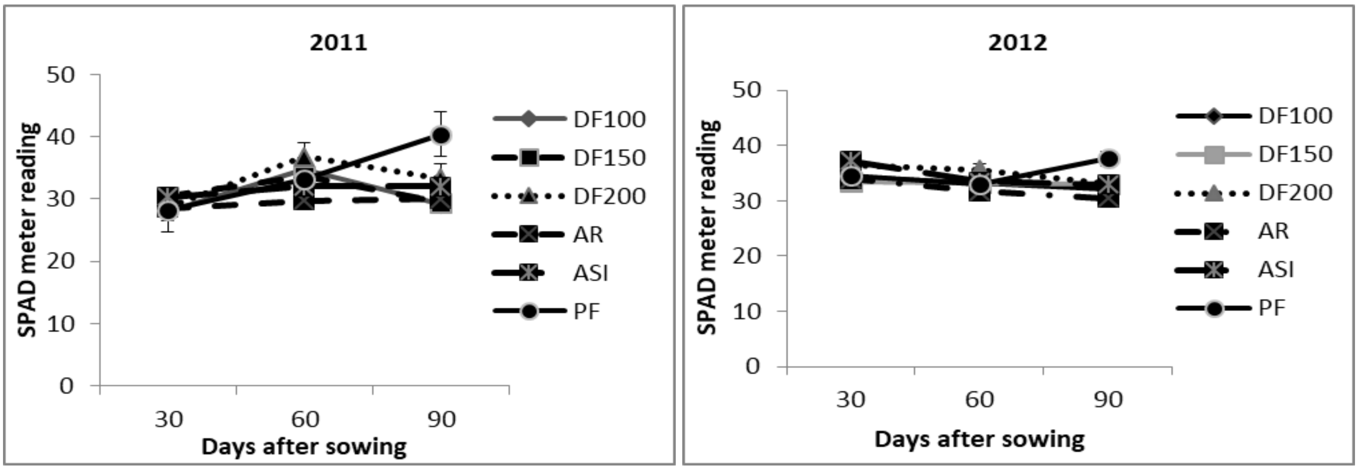


Fig 6: SPAD reading of rice under different irrigation treatments. Bars indicate the standard errors

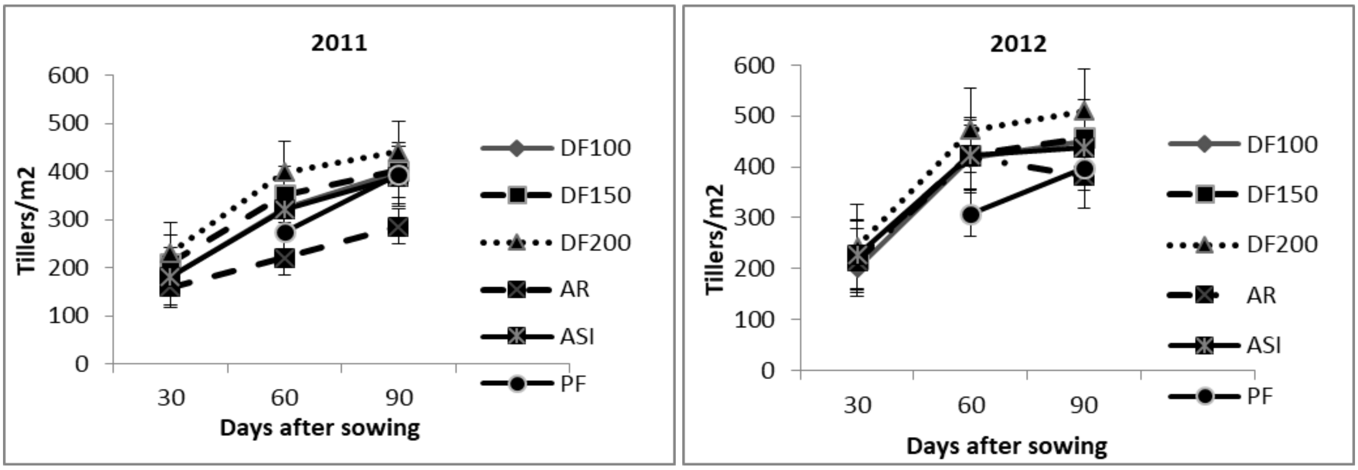


Fig 7: Tiller production in rice under different irrigation treatments. Bars indicate the standard errors

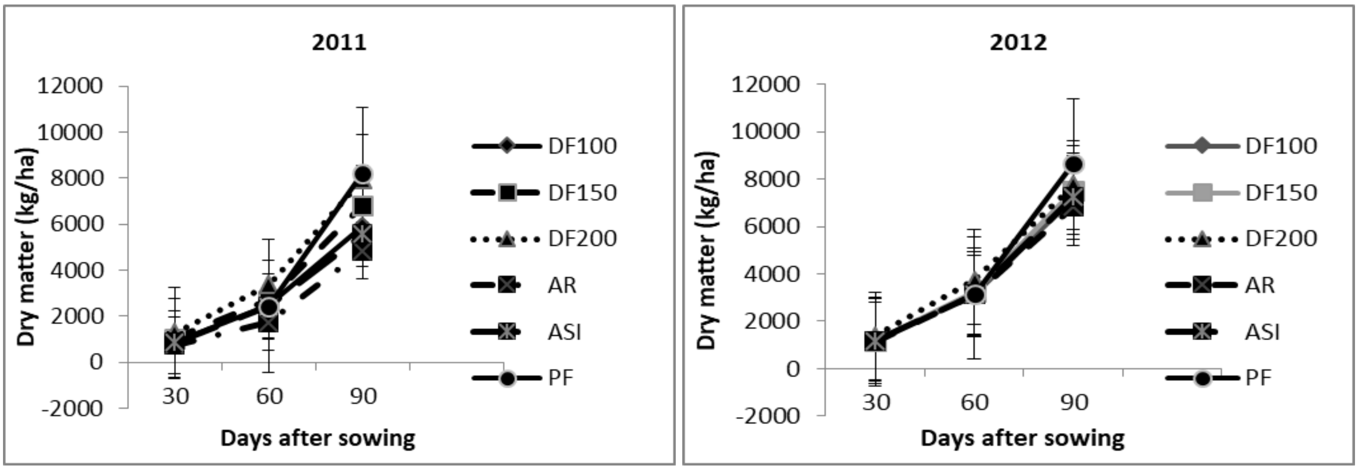


Fig 8: Dry matter production in rice under different irrigation treatments. Bars indicate the standard errors

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