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Venkataravana Nayaka GV
Ph.D., Scholar, Department of Agronomy, ICAR-Indian Institute of Rice Research, Hyderabad, Telangana, India

Dr. Prabhakara Reddy G
Associate Dean, Agricultural College, Mahanadi, ANGRAU, Andhra Pradesh, India

Mahender Kumar R
Principal Scientist, Department of Agronomy, ICAR-Indian Institute of Rice Research, Hyderabad, Telangana, India

Corresponding Author:
Venkataravana Nayaka GV
Ph.D., Scholar, Department of Agronomy, ICAR-Indian Institute of Rice Research, Hyderabad, Telangana, India

Performance of rice under different irrigation regimes: A review

Venkataravana Nayaka GV, Prabhakara Reddy G and Mahender Kumar R

Abstract
Food security in India is closely linked to sustainable rice production as it contributes to more than 42 per cent of the total food grain production and is the staple food for more than two thirds of Indian population. However, adequate water availability for rice production is becoming a major problem owing to depleting groundwater levels, water quality degradation and rising demands from other sectors. Rainfall patterns in many areas are becoming more unreliable, with extremes of drought and flooding occurring at unexpected time. Rice systems provide a major source of calories for more than half of the world‟s population; however, they also use more water than other major crops. Irrigated lowland rice not only consumes more water but also causes wastage of water resulting in degradation of land. Among the different water-saving irrigation methods in rice, the most widely adopted is alternate wetting and drying (AWD). Many of the rice cultivars vary in their performance under different Irrigation regimes and systems of cultivation.

Keywords: Irrigation regimes, alternate wetting and drying, water use efficiency and continuous flooding

1. Introduction
Water resources, both surface and underground are contracting and water has become a restricting element in rice production (Farooq *et al.*, 2009). Because of expanding shortage of freshwater assets accessible irrigated agriculture and heightening demand of food around the globe in the future, it will be important to produce more food with less water. Since, more irrigated land is dedicated to rice than to some other crops in the world, wastage of water asset in the rice field ought to be limited (IRRI, 2004). Further, Tuong and Bouman (2005) [9] estimated that by 2025, 2 million ha of Asia‟s irrigated dry-season rice and 13 million ha of its irrigated wet-season rice may experience "physical water scarcity" and most of the irrigated rice, approximately 22 million ha, in South and Southeast Asia may suffer "economic water scarcity". The generally accepted fact is that no new water can be made than what we have at present; for that reason, to conserve what is accessible and subject judicious utilization of each drop of water is the brilliant guideline and rice cannot be an exception. Consequently, while supporting increasing productivity of irrigated rice, it is essential to fulfill the future needs of 130 million tons of rice by 2025. There is a quick need to decrease and optimize irrigation water use in the light of declining water accessibility for agriculture in general and to rice in specifically. Since irrigated rice production is the main consumer of water in the agricultural sector and country‟s most extensively consumed staple crop, finding approaches to reduce the requirement for water to grow irrigated rice should profit both producers and consumers contributing to water security and food security. To beat this issue and increase the rice grain production to meet the food security we have to develop novel technologies that will sustain or enhance the rice production by increasing irrigation efficiencies. If rice is grown under traditional conditions, farmers resort to continuous submergence irrigation resulting in gigantic wastage of water and lower water use efficiency. Hence it becomes essential to develop and adopt strategies and practices for more efficient use of water in rice cultivation.

2. Growth parameters of rice under different irrigation regimes
2.1 Plant height
Kishore (2016) [38] from Hyderabad reported that among the different irrigation regimes, maintenance of continuous submergence depth of 3 cm from transplanting to PI and 5 cm from PI to physiological maturity (PM) registered significantly superior performance in terms of plant height over rest of the irrigation regimes except that it was on par with flooding to a water depth of 3 cm between 15 DAT to physiological maturity. At all the growth stages except at 30 DAT, the maximum plant height (51.45, 87.47, 107.03 and 111.40 cm at 30, 60, 90 DAT and at harvest, respectively) was recorded in the treatment which received irrigation

to 2.5 cm depth immediately after disappearance of ponded water at zero DADPW *i.e.,* on the same day when the ponded water disappeared and the minimum was in the treatment where in 6 DADPW (Chowdhury *et al.,* 2014) [21]. The highest plant height was obtained when the field was under continuous flow of water, but as the plant growth progressed toward maturity, the water depths of 15 - 20 cm produced significantly taller plants than the other treatments at National Cereals Research Institute, Badeggi, Nigeria (Ismaila *et al*., 2014) [35]. Rahaman and Sinha (2013) [58] in West Bengal revealed that significantly higher plant height was recorded at saturation (93.65 cm) as compared to farmers practice (93.16) and intermittent ponding (2 DAD) from 15 to 35 DAT followed by continuous ponding (92.15) on silty clay soil.

In Faizabad, Uttar Pradesh, a field experiment conducted during *kharif* 2010 on silt loam soils by Kumar *et al*., (2013) [41] revealed that there was significantly higher plant height (125.17 cm) in 7 cm irrigation at 1 day after disappearance of ponded water (DADPW) compared to 7 cm irrigation at 3 DADPW (116.08 cm) and 5 DADPW (113.39 cm). Dass and Chandra (2012) [23] from Pantnagar, Uttarakhand, during *kharif* 2008 and 2009 revealed that applying irrigation at 1 or 3 days after disappearance of standing water (DADSW) resulted in significantly taller plants compared to 5 DADSW. The maximum plant height was recorded in irrigation at one day after disappearance of water which was statistically at par with irrigation at two days after disappearance of water and tensiometer guided irrigation (soil matric tension of 150 ± 20 cm) at Ludhiana in loamy sandy soils (Sandhu *et al*., 2012) [66]. An experiment was conducted in north Iran in loam soils by Azarpour *et al*. (2011) [4] and revealed that there was no significant difference in plant height between submergence (139.9 cm) and 5 days interval irrigation (138.2 cm).

Maragatham and Martin (2010) [47] reported that the AWD irrigation practice was comparatively more effective in recording higher plant height than the aerobic rice and flooded rice. The growth of rice under field capacity condition was significantly affected as indicated by shorter plants at maturity regardless of planting season and location as compared with other treatments. Plants were in the range of 9 - 13 per cent shorter under field capacity than flooded conditions in Kuala Lumpur, Malaysia on silty clay soils (Sariam and Anuar, 2010) [67]. The experiment conducted at Rice Research Institute, Rasht, Iran during 2006 and 2007 years by Rezaei *et al*. (2009) [64] revealed that there was no significant difference in plant height between continuous submergence irrigation (139 cm) and 5 and 8 days interval irrigation (137 cm and 136 cm, respectively). Ramakrishna *et al.* (2007) [62] observed in a two year study, at IARI New Delhi, the maximum plant height of rice was with continuous submergence (96.8 cm and 99 cm) which was significantly superior over 3 - day drainage (91.6 cm and 95.3 cm) but was on a par with that of 1 day drainage (94.8 cm and 96.9 cm during 2005 and 2006, respectively). Sariam *et al.* (2007) [69] observed that plants were shorter by 5.5 per cent when rice was grown under field capacity than under flooded conditions. Sariam (2004) [68] observed that plants were shorter by 5.5 per cent when rice was grown under field capacity than under flooded conditions.

2.2 Number of tillers

Sathish (2015) [72] concluded at Hyderabad that among the different irrigation regimes significantly higher number of tillers m^{-2} was recorded with recommended submergence of 2 - 5 cm water level as per crop stage over AWD irrigation of 5 cm submergence when water level falls below 10 cm in field water tube and was on par with irrigation of 5 cm at 3 DADPW and 5 cm submergence with 5 cm drop of water level in the field water tube on sandy loam soil. The highest number of tillers m^{-2} (313) in hybrid rice was obtained with maintaining continuous submergence of 5 ± 2 cm of water which remained on par with that obtained under irrigation given at 1 day after disappearance of ponded water (310) but superior over 3 days after disappearance of ponded water (297) in clay soils of Chhattisgarh (Pandey *et al*., 2010) [52]. Among the irrigation regimes, flooded condition (48.7 cm) recorded 12.2 per cent higher plant height and 30.7 per cent higher tiller number (585.4 m^{-2}) compared to aerobic cultivation (43.4 cm and 447.8 m^{-2}, respectively) (Patel *et al.*, 2010) [54]. Geethalakshmi *et al.* (2009) [30] confirmed that maximum number of tillers m^{-2} and higher shoot length was recorded under intermittent irrigation compared to 5 cm depth at one DADPW and to 5 cm depth at two DADPW.

At Asian Institute of Technology, Thailand applying irrigation for two weeks followed by two weeks no irrigation produced significantly higher number of total tillers at harvest (20.8 ± 0.9) than conventional water management and one-week irrigation followed by 3 weeks no irrigation (Ginigaddara and Ranamukhaarachchi, 2009) [31]. Kumar *et al.* (2013) [41] recorded more number of tillers m^{-2} (145.96) with 7 cm irrigation at 1 DADPW which was significantly superior to 7 cm irrigation at 3 (130.06) and 5 (113.61) DADPW. Continuous submergence recorded higher number of tillers than 1 day drainage, followed by 3 day drainage, but the differences were statistically non significant on sandy clay loam soils of IARI, New Delhi (Ramakrishna *et al*., 2007) [62]. In the same way at Raipur, applying irrigation at 1, 3 or 7 days after disappearance of ponded water (DADPW) produced statistically similar number of tillers hill^{-1} in medium duration variety Kranti (Pandey *et al*., 2006) [51]. Balasubramanian and Krishnarajan (2000) [5] observed highest number of tillers in rice which received irrigation of 5 cm depth at one DADPW and irrigation of 2.5 cm depth at 3 DADPW noticed moisture stress.

2.3 Dry matter production

Sathish *et al.* (2016) [73] from Hyderabad reported that among the different irrigation regimes recommended submergence of 2 to 5 cm water level as per crop stage recorded significantly higher dry matter production at all the stages of crop and was on par with AWD irrigation of 5 cm submergence depth with 5 cm drop of water level in the field tube and 3 DADPW at 80 and 110 DAS. Geethalakshmi *et al.* (2009) [30] conducted experiment in sandy clay loam soils at Agriculture College and Research Institute, Tamil Nadu Agricultural University, Coimbatore and confirmed that the maximum dry matter production, higher shoot and root length were recorded under SRI method of irrigation (intermittent irrigation) compared to 5 cm depth at one day after disappearance of water and 5 cm depth at two days after disappearance of water. A field experiment was conducted at Annamalai University experimental farm with clay loam soils and observed that there was increased total dry matter production in AWD irrigation system (Rajesh and Thanunathan, 2003) [61].

2.4 Phenology

Ismaila *et al.* (2014) [35] conducted an experiment at Edozhigi lowland Rice Research field of National Cereals Research Institute, Badeggi, Bida, Nigeria and observed that days to 50 per cent flowering were attained earlier in the plots that were not flooded. The alternate wetting and drying interval treatments took 2-3 days more time to begin flowering, but took 3-5 days less time to mature. Panicle initiation was delayed by 1 to 2 and 6 to 7 days due to water regimes from continuous submergence to irrigation at 1 and 3 days after disappearance of ponded water, respectively (Chapagain and Yamaji, 2010) [19]. In rice, 50 per cent flowering was delayed by 3 - 4 days in irrigation at 3 days after disappearance of ponded water and further it was noticed that the crop maturity was delayed by 8 to 11 days due to change in soil water regimes at Pantnagar on sandy loam soils (Rai and Kushwaha, 2008) [60].

3. Physiological Studies of rice under different irrigation regimes

3.1 Physiological growth parameters

The maximum leaf area index was recorded in irrigation one day after disappearance of water (2.65) which was statistically at par with irrigation two days after disappearance of water (2.63) and tensiometer guided irrigation (soil metric tension of 150 ± 20 cm) (2.60) at Ludhiana in loamy sand with alkaline soil (Sandhu *et al*., 2012) [66]. Kumar *et al*. (2013) [41] at Faizabad, Uttar Pradesh on silt loam soils observed that the highest leaf area index (5.20) and dry matter accumulation (17.54 g) with 7 cm irrigation 1 DADPW which was found significantly superior to 7 cm irrigation at 3 and 5 DADPW. Experiments conducted in Samastipur, Pusa, Bihar by Chowdhury *et al*. (2014) [21] observed that the leaf area index and crop growth rate (CGR) were maximum with 2.5 cm irrigation 0 days after disappearance of ponded water (DAD) over 6 DAD but both were at par with 3 DAD. Maragatham and Martin (2010) [47] reported that the AWD irrigation practice recorded higher dry matter production than the aerobic rice and flooded rice.

3.2 SPAD chlorophyll meter reading (SCMR)

Maintenance of continuous submergence depth of 3 cm from transplanting to PI and 5 cm from panicle initiation to physiological maturity resulted in significantly superior performance of SPAD readings and LCC rating at different growth stages over rest of the irrigation regimes (Kishore, 2016) [38]. Cabangon *et al.* (2011) [16] concluded that a combination of AWD and SPAD based N management, at critical value of 38 can save irrigation water and N fertilizer while maintaining high yield as in continuous flooding (CF) conditions with fixed time and rate of nitrogen application (180 kg ha^{-1}).

3.3 Relative water content (RWC)

Among the different irrigation regimes there was not much variation in RWC in recommended submergence of 2 to 5 cm water level as per crop stage (99.6%) and irrigation of 5 cm, when water level falls below 5 cm from soil surface in field water tube (98.5%) and irrigation of 5 cm at 3 DADPW (97.6%) treatments on sandy loam soil at Hyderabad but shown high variation with irrigation of 5 cm, when water level falls below 10 cm from soil surface in field water tube (91.3%) (Sathish *et al*., 2017a) [74]. Kishore (2016) [38] reported that among the different irrigation regimes, relative water content was higher in continuous submergence depth of 3 cm from transplanting to PI and 5 cm from PI to physiological maturity, comparable values of RWC were also registered when the crop was flooded to a water depth of 5 cm between 15 DAT to PM as and when ponded water level drops to 5 cm below ground level in field water tube and 10 cm below ground level in field water tube.

4. Yield Parameters of rice under different irrigation regimes

Kishore (2016) [38] from Hyderabad found that among the different irrigation regimes, yield attributes *viz*., number of panicles m^{-2}, panicle weight, total number of grains panicle^{-1}, number of filled grains panicle^{-1} and test weight registered with continuous submergence depth of 3 cm from transplanting to PI and 5 cm from PI to PM were significantly superior over other AWD irrigation regimes. Sathish (2015) [72] on sandy loam soil at Hyderabad during *kharif* reported that among the different irrigation regimes recommended submergence of 2-5 cm water level as per crop stage registered significantly more number of panicles (304) m^{-2} and higher filled grains (306) panicle^{-1} as compared to AWD irrigation of 5 cm when water falls below 10 cm from soil surface and was on par with AWD irrigation of 5 cm, when water level falls below 5 cm from soil surface in field water tube (288 panicle m^{-2}). Among the different moisture regimes, the highest number of panicles m^{-2} (121.54), length of the panicle (22 cm), number of grains panicle^{-1} (180.14) and weight of grains panicle^{-1} (4.34 g) were recorded with the application of 7 cm irrigation at 1 DADPW, which was significantly superior over the 7 cm irrigation at 3 and 5 DADPW at Agronomy Research Farm, Narendra Deva University of Agriculture and Technology, Faizabad, Uttar Pradesh (Kumar *et al*., 2014) [21, 40]. Rahaman and Sinha (2013) [58] revealed that saturation recorded significantly higher number of panicles m^{-2} (312.7), grains panicle^{-1} (102.7), panicle length (26.29 cm), panicle weight (3.26 g) and test weight (21.62 g) as compared to continuous ponding (CP) or farmers practice and intermittent ponding (2 DAD 5 ± 0) from 15 to 35 DAT followed by CP.

The maximum number of panicles m^{-2}, weight of grains panicle^{-1} and panicle length were observed in irrigation at one day after disappearance of water and it was statistically at par with irrigation at two days after disappearance of water at Ludhiana on loamy sand with alkaline soil (Sandhu *et al*., 2012) [66]. Zhang *et al*. (2012) [89] reported that rice grain filling rate in AWD irrigation practice was high at the early grain filling stage and low at the late grain filling stage, but under continuous flooding condition grain filling rate of rice was still high at the late grain filling stage also. Significantly higher test weight of rice (28.03 g) was noticed in 5 days interval irrigation compared to continuous submergence (Azarpour *et al*., 2011) [4]. Bayayoko *et al*. (2010) [6] from Niono, Nigeria, reported that significantly higher number of panicles per 10 hills were recorded in non-flooded plot (235) compared to flooded plot (148). Pandey *et al*. (2010) [52] reported that the irrigation schedule of 1 DADPW up to 25 days after flowering produced the highest number of grains panicle^{-1}, 1000-grain weight and reduced sterility percentage as compared to irrigation schedule of 7 DADPW up to 20 days after flowering, while irrigation schedule at 3 DADPW was similar to 1 DADPW for the above parameters.

Continuous submergence registered higher number of panicles hill^{-1}, grains panicle^{-1} and panicle length over 3 day drainage in sandy clay loam soils of IARI, New Delhi (Ramakrishna *et al*., 2007) [62]. Rezaei *et al*. (2009) [64] at Rasht, Iran observed that continuously submerged irrigation or 5 day and 8 day interval had no significant effects on number of panicles, fertility percentage of grain, number of filled and unfilled grains, panicle length and weight of 100 grains. Similar results were also reported by Luikham and Anal (2008) [44]. Patel (2000) [55] observed more filled grains panicle^{-1} and 1000 grain weight when the irrigation was in the order of saturation up to tillering followed by submergence till ripening in rice. Luikham and Krishnarajan (2005) [45] reported that though the number of panicles (454), number of spikelets (73) and number of filled grains (55) were recorded maximum with irrigation on the day of disappearance it remained on par with irrigation one DADPW (428, 71 and 53, respectively).

4.1 Grain and straw yield of rice under different irrigation regimes

A field experiment conducted on sandy loam soil at Hyderabad revealed, that recommended submergence of 2 - 5 cm water level as per crop stage recorded significantly higher grain yield of 6148 kg ha^{-1} and straw yield of 7039 kg ha^{-1} which was on par with irrigation of 5 cm at 3 DADPW (Sathish, 2015) [72]. Kumar *et al.* (2014) [21, 40] opined that grain yield was higher by 10.92 per cent and 14.12 per cent in 7 cm irrigation at 1 DADPW as compared to 7 cm irrigation at 3 and 5 DADPW, respectively. Rahman and Sheikh (2014) [59] reported that the grain yield was increased significantly with increasing levels of irrigation. The respective increase in grain yield of rice due to 2.5 cm irrigation at zero DADPW and 3 DADPW as compared to 6 DADPW was to the tune of 14.87 and 8.77 per cent, respectively. While the respective straw yields recorded were 7.4, 7.2 and 6.8 t ha^{-1} due to 2.5 cm irrigation at 0 DADPW, 3 DADPW and 6 DADPW, respectively. At Mwea, in Kenya, Omwenga *et al*. (2014) [50] revealed that the 8 days drying period gave the highest yield of 7.13 t ha^{-1} compared with the conventional method of growing rice which gave a yield of 4.87 t ha^{-1}.

Ashouri (2014) [2] reported that the effect of irrigation regimes on grain yield were significant and the irrigation interval of 5, 8 days and continuous submergence produced statistically similar grain yield (7342, 7079 and 7159 kg ha^{-1}, respectively) while the grain yield was decreased in irrigation interval of 11 days (5168 kg ha^{-1}). The conventional method of irrigation practice though produced higher grain and straw yields, it was comparable with AWD irrigation regime of 5 and 10 cm drop of water table (Kannan, 2014). In West Bengal, Rahaman and Sinha (2013) [58] observed that saturation recorded significantly higher grain and straw yields (4.26 and 6.14 t ha^{-1}) than continuous ponding (CP) or farmers practice (4.06 and 5.73 t ha^{-1}) and intermittent ponding (2 DAD 5 ± 0) from 15 to 35 DAT followed by CP (4.01 and 5.64 t ha^{-1}). In Gazipur, Bangladesh Paul *et al*. (2013) [56] observed higher grain yield (5.9 - 6.2 t ha^{-1}) in irrigation when water level reached 15 cm below ground level and the lower (4.6 - 4.7 t ha^{-1}) was in irrigation when water level reached 50 cm below ground level.

Pasha *et al.* (2012) [53] conducted an experiment in Nalgonda district of Telangana on sandy clay loam soils and reported observed that SRI recorded highest grain yield during 2008 and 2009 (6461 and 7017 kg ha^{-1}) followed by rotational system of irrigation (6242 and 6429 kg ha^{-1}) as compared to farmers practice of growing rice with continuous flooding. SRI also resulted in irrigation water saving over farmer practice of flood irrigation. A parallel work carried out by Sandhu *et al.* (2012) [66] revealed that the maximum grain yield (6.99 t ha^{-1}) was obtained with the application of irrigation one day after disappearance of water which was at par with irrigation at three days after disappearance of water (6.87 t ha^{-1}) and tensiometer guided irrigation (6.85 t ha^{-1}). Applying irrigation water of 6 cm depth at 1 DADSW resulted in significantly higher grain (6.32 t ha^{-1}) and straw yield (9.64 t ha^{-1}) at Pantnagar, compared to 5 DADSW (5.82 t ha^{-1} and 8.80 t ha^{-1} grain and straw yield, respectively) and was on par with 3 DADSW (Dass and Chandra, 2012) [23]. Navabian *et al.* (2011) [49] suggested that 8 days irrigation interval at 5 cm depth is optimum for getting higher yield at North Iran. Rice grown with AWD techniques recorded higher yield than continuously flooded rice even though both the treatments recorded similar above ground biomass (Yang and Zhang, 2010) [86].

The grain yield was higher under saturated condition (7.6 t ha^{-1}) than flooded condition (7.1 t ha^{-1}) in Malaysia (Sariam and Anuar, 2010) [67]. Pandey *et al.* (2010) [52] at Chhattisgarh obtained the highest grain yield (7.0 t ha^{-1}) of summer hybrid rice with maintaining continuous submergence (CS) of 5 ± 2 cm of water and which remained on par with the yields obtained under irrigation given at 1 DADPW (6.8 t ha^{-1}). Zhao *et al.* (2010) [90] reported 26.4 per cent higher yield under SRI intermittent irrigation as against traditional flooding. Dhar *et al.* (2008) [24] at Jammu revealed that the maximum grain yield of rice was recorded under SRI methods (5.29 t ha^{-1}), while the yield of crop irrigated at 7 DADPW was significantly higher than the yield obtained from other treatments like AWD, applying irrigation at 3, 5 and 9 DADPW, but similar to the yield obtained from continuous submergence (4.93 t ha^{-1}). Continuous water submergence gave the highest grain yield than the grain yield obtained under 3 day drainage and 1 day drainage (Ramakrishna *et al.*, 2007) [62].

Avil *et al.* (2006) conducted an experiment at Jagtial, Telangana in red sandy loam soils and reported that the grain and straw yields were significantly influenced by different irrigation schedules. Maximum grain yield (4240 kg ha^{-1}) was recorded with daily irrigation (continuous submergence) and it was significantly superior to the remaining treatments *viz.*, irrigation once in 4 days (3710 kg ha^{-1}), irrigation once in 5 days (3350 kg ha^{-1}), irrigation once in 6 days (3020 kg ha^{-1}), irrigation for 5 days and no irrigation for 5 days (3800 kg ha^{-1}) and irrigation for 7 days and no irrigation for 7 days (3610 kg ha^{-1}). Experiments on AWD irrigation indicated that there was no yield decline beyond a reduction in water input of 20 per cent and the yield reduction was 25 per cent at 60 per cent reduction in water input (Bindraban *et al*., 2006) [10]. A study conducted by Makarim *et al.* (2002) [46] at South Sulawesi, Indonesia revealed that the intermittent irrigation produced significantly higher grain yield (7110 kg ha^{-1}) against continuous irrigation (6750 kg ha^{-1}). Chandrasekaran *et al*. (2002) [18] in Mohanpur, West Bengal concluded that the irrigation scheduled at 5 cm depth at one DADPW was optimum to obtain higher yields in rice-rice cropping system.

Rashid and Khan (2001) [63] found that different irrigation regimes *viz.*, continuous water (1 - 7 cm depth), shallow standing water (1 - 2 cm depth) to saturation and irrigation water application (5 - 7 cm depth) at 3 days after disappearance of standing water (DADSW) did not differ significantly with respect to grain yield of rice. Irrigation to rice two DADPW at vegetative phase was found to be the best irrigation practice for getting higher grain yield (Patel, 2000) [55]. The lower rice yield (58% lower than the flooded rice) was observed in AWD water management practice (Grigg *et al*., 2000) [32]. Das *et al.* (2000) [22] revealed that irrigation scheduling at 3 DADPW either at 7 or 5 cm depth of ponding recorded higher grain and straw yields over 5 DADPW at similar depth of irrigation. Singh and Ingram (2000) [77] observed that maintaining saturated soil moisture condition produced higher yield over stress given at different stages of crop growth. Ganesh (2000) [28, 29] concluded that KRH - 2 rice hybrid gave significantly higher grain yield (6800 kg ha^{-1}) under field capacity to saturation moisture regime which was 14 per cent higher when compared to the yield obtained by maintaining 2.5 cm submergence from the date of transplanting to 20 DAT fallowed by maintaining 5 cm submergence till 15 days before harvest (5920 kg ha^{-1}).

5. Water Productivity and Water Use Studies of rice under different irrigation regimes

Sathish *et al.* (2017b) [75] in Hyderabad reported that the different irrigation practices significantly influenced the WUE of rice crop. The WUE was higher in the treatment with irrigation of 5 cm when water level falls below 10 cm from soil surface in field water tube, which registered 4.9 kg ha mm^{-1} and was on par with irrigation of 5 cm at 3 DADPW (4.8 kg ha mm^{-1}) and irrigation of 5 cm when water level falls below 5 cm from soil surface in field water tube with (4.5 kg ha mm^{-1}). The lowest WUE (3.5 kg ha mm^{-1}) was accounted with recommended submergence of 2 - 5 cm water level as per crop stage. Kishore (2016) [38] concluded from a field experiment on sandy loam soils at Hyderabad that water productivity was inversely related to water input. Continuous submergence maintaining 3 cm from transplanting to panicle initiation stage and there after 5 cm up to physiological maturity recorded the lowest water productivity as compared to AWD irrigation regime. Field experiment at Hyderabad on sandy loam soils indicated that the WUE was higher with the irrigation of 5 cm when water level falls 5 or 10 cm below soil surface in field water tube (4.5 or 4.9 kg mm^{-1}) and was on par with irrigation of 5 cm at 3 DADPW (4.8 kg mm^{-1}) (Sathish, 2015) [72]. Shantappa (2014) [76] conducted an experiment in clay loamy soils of DRR farm, Hyderabad and reported that there was significant improvement in WUE to the tune of 39 per cent under intermittently irrigated SRI over continuously flooded NTP. Continuous submergence consumed the highest total water use (122.2 cm) and produced the lowest grain yield (4.71 t ha^{-1}) resulting in the lowest WUE (84.34 kg ha cm^{-1}).

Application of irrigation water of 5 cm depth when water level in PVC pipe fell to 15 cm below ground level recorded the highest WUE (85.55 kg ha^{-1} cm) along with water saving (15 cm) compared to continuous submergence (Rahman and Sheikh, 2014) [59]. Nearly 20 to 47 per cent of irrigation water used for rice production under continuous flooding was reduced under intermittent irrigation of 3 - 7 cm depths without any significant reduction in rice grain yield (Fonteh *et al*., 2013) [27].

Irrigation at two days after disappearance of water and tensiometer guided irrigation resulted in numerically similar water productivity (0.43 kg m^{-3}) but they differed significantly from other irrigation schedules at Ludhiana in loamy sand with alkaline soil (Sandhu *et al*., 2012) [66]. Cabangon *et al.* (2011) [16] also reported re-irrigating the field when plots showed mild stress in AWD practice reduced irrigation water input by 8 - 20 per cent and at severe stress by 19 - 25 per cent as compared to continuous flooding. Kulkarni (2011) [39] reported that using of field water tube in AWD irrigation was safe and save the water use up to 25 per cent without reduction in rice yield. Chapagain and Yamaji (2010) [19] reported higher water productivity (1.74 g l^{-1}) in AWD compared to continuously flooded rice (1.23 g l^{-1}). Mostafazadeh *et al*. (2010) [48] reported that decreasing the depth of ponded water on the soil surface in irrigated rice reduced the water use by about 23 per cent. The irrigation schedule of one day after disappearance of ponded water required 604 mm less irrigation water than that of maintaining continuous submergence.

Irrigation at one day after disappearance of ponded water recorded higher water use efficiency (76 kg ha mm^{-1}) over continuous submergence in clayey soils at Chhattisgarh (Pandey *et al*., 2010) [52]. Saving of irrigation water and enhancement of water use efficiency was the highest when irrigation water was given four days after disappearance of standing water and the yield decrease due to intermittent flooding was not significant (Singh *et al.*, 2010) [78]. Rezaei *et al*. (2009) [64] in Rasht, Iran showed that irrigation interval decreased the water use, but increased the water productivity in five and eight days interval irrigation by 40 per cent and 60 per cent, respectively as compared to full irrigation without any yield loss. An experiment was conducted in sandy clay loam soils at Agriculture College and Research Institute, Tamil Nadu Agricultural University, Coimbatore and revealed that water savings under SRI was to the tune of 12.6 and 14.8 per cent, respectively during summer and *kuruvai* seasons. Impounding of 2.5 cm of irrigation water and irrigation after formation of hairline cracks have shown considerable water saving besides better root environment under SRI (Geethalakshmi *et al*., 2009) [30]. Huan *et al.* (2008) [33] recorded the highest water productivity with AWD irrigation and the lowest water productivity was with flooded rice.

Saving of irrigation water and enhancement of water use efficiency were highest when irrigation water was given four days after disappearance of standing water (Swarup *et al.*, 2008) [81]. In New Delhi, Ramakrishna *et al*. (2007) [62] opined that maximum irrigation water productivity (kg grain m^{-3} water used) of 0.35 and 0.63 and field crop water productivity of 0.42 and 0.37 were obtained with three days drainage followed by one day drainage and the least was with continuous water submergence. Based on experiments with AWD in lowland rice areas in China and Philippines, Bouman and Tuong (2007) [13, 14] reported that total (irrigation + rainfall) water inputs decreased by around 15 - 30 per cent without a significant impact on yield. Continuous water submergence recorded more irrigation requirement (1,200 and 1,080 mm) compared with one day drainage (840 and 680 mm) and three day drainage (600 and 560 mm) in first and second year of study, respectively. Reductions in irrigation water requirement under AWD by 40 - 70 per cent, 20 - 50 per cent, and more than 50 per cent, respectively compared to continuous flooding of rice crop was noticed by Keisuke *et al*. (2007) [37] and Zhao *et al*. (2010) [90].

Alternate Wetting and Drying practice tackles the water scarcity in irrigated rice cultivation and enables more effective water and energy use there by the water productivity increases compared to conventional cultivation (Lampayan *et al*., 2009 and Bouman *et al*., 2007) [42, 13, 14]. Belder *et al.* (2004) [7] quantified that evaporation losses in rice fields were decreased by 2-33 per cent in AWD compared with continuously flooded condition. Maximum irrigation water productivity (0.35 and 0.63 kg m^{-3}) and field-crop water productivity (0.42 and 0.37 kg m^{-3}) was observed with three days drainage and one day drainage, respectively and the least were observed with continuous water submergence (0.32 and 0.28 kg m^{-3}). Cabangon *et al*. (2004) [7] reported that there could be water saving to the tune of 15 to 20 per cent in rice through AWD without a significant impact on yield. Irrigation water saving in the alternately submerged and non submerged treatments were in the range of 13 - 16 per cent as compared to the continuously submergence regime and the rice grain yields were not significantly affected by the water regimes but significantly higher water productivity was noticed in the alternately submerged and non submerged regime than in the continuously submergence regime (Belder *et al*., 2002) [8].

Thiyagarajan *et al.* (2002) [83] reported that limited irrigation of 2 cm depth after crack development recorded higher water productivity (0.732 kg m^{-3}) with 56 per cent saving in irrigation water compared to CF of 5 cm standing water without any significant reduction in grain yield in sandy clay loam soils of Coimbatore. Hugh *et al.* (2002) [34] found that in SRI method with alternate wetting and drying irrigation used 19 - 55 per cent less water than conventional method depending on the permeability of the soil.

Tabbal *et al.* (2002) [82] reported that maintaining a very thin film of water layer at saturated soil condition or alternate wetting and drying can reduce water requirement by almost 40 - 70 per cent over traditional practice of continuous submergence without any significant yield loss. Ganesh and Hakkali (2000) [28, 29] found that the application of irrigation once in 3 to 5 days with 5 cm submergence when irrigation was given immediately after DADPW or 1 to 2 days later saved the water to the extent of 49 per cent over the existing practice of continuous submergence without reducing grain and straw yields. Patel (2000) [55] observed a higher WUE of 3.04 kg grain ha mm^{-1} in rice when continuous saturation level was maintained. Irrigation once in 7 days to maintain field saturation consumed the lowest amount of water (80.30 cm) and saved 41 per cent of irrigation water over 2.5 to 5.0 cm submergence till 15 days before harvest without any significant reduction in grain yield (Ganesh, 2000) [28, 29].

6. Nutrient Uptake and Nutrient Use Studies of rice under different irrigation regimes

Sathish *et al.* (2016) [73] concluded that among the different irrigation regimes. N, P and K uptake was significantly higher at flowering (105, 109.4 and 17.09 kg ha^{-1}) and harvesting (31.68, 55.86 and 57.57 kg ha^{-1} respectively) stage with recommended submergence of 2 - 5 cm water level as per crop stage over irrigation of 5 cm, when water level falls below 10 cm from soil surface in field water tube on sandy loam soils at Hyderabad and was on par with irrigation of 5 cm, when water level falls below 5 cm from soil surface in field water tube (90, 95.20 and 15.09 at flowering, 25.96, 45.75 and 50.61 kg ha^{-1} respectively). The NPK uptake was the lowest in AWD irrigation regime of 3 cm submergence depth from 15 DAT to physiological maturity when the ponded water level drops to 15 cm below ground level in the field water tube AWD regime on sandy loam soils of Hyderabad (Kishore, 2016) [38]. Chowdhury *et al.* (2014) [21] reported that irrigation and nutrient levels significantly influenced the N, P and K contents in rice grain and straw and the maximum NPK uptake (63.49, 19.19 and 14.95 NPK kg ha^{-1} respectively) were noticed in the treatment which received the maximum number of irrigations (45) and the lowest (53.79, 14.06 and 10.86 NPK kg ha^{-1}) was with the minimum number of irrigations (15).

Kumar *et al*. (2014) [21, 40] observed that maximum N, P and K uptake (100, 39.12 and 89.41 kg ha^{-1}, respectively) was recorded under 7 cm irrigation at 1 day after disappearance of ponded water, which was found significantly superior over 7 cm irrigation at 3 and 5 DADPW. In alternate wetting and drying, agronomic N use efficiency (AEN, kg grain kg^{-1} N applied), N recovery efficiency (REN%) and partial factor productivity of N (PFPN, kg grain kg^{-1} N applied) calculated were significantly increased by 6.1 per cent, 5.1 per cent and 5.7 per cent during 2010 and 8.9 per cent, 6.1 per cent and 6.9 per cent during 2011, respectively over conventional flooding (Ye *et al*., 2013) [88]. Significantly the highest PFP (partial factor productivity) of nitrogen was recorded in saturation (71.0 - 72.0 kg grain kg^{-1} of N) due to higher grain yield obtained from that treatments in comparison to farmers practice and intermittent ponding (2 DAD 5 ± 0) from 15 to 35 DAT followed by CP (Rahaman and Sinha, 2013) [58]. Uptake of nutrients, especially N and P in grains and straw were higher with irrigation at 1 and 3 day after disappearance of standing water than at 5 days after disappearance of standing water at Pantnagar in young alluvial soils (Dass and Chandra, 2012) [23]. Dong *et al.* (2012) [25] also noticed that even though loss of fertilizer N through nitrification and denitrification was higher under AWD than CF (0.22 vs. 0.04 g N m^{-2}), it removed only 2.5 per cent of the total applied N fertilizer and was thus quantitatively insignificant and negligible.

Growing of rice under AWD could consequently lead to a greater loss of applied fertilizer N and soil N compared to rice grown under continuous flooding conditions and the latter itself has been characterized by having low N use efficiency (Peng *et al*., 2011) [57]. Buresh *et al.* (2008) [15] observed the low fertilizer use efficiency in AWD practice because of periodic soil aeration leading to higher nitrogen losses through nitrification and denitrification processes. Biswas *et al.* (2007) [11] reported that at IARI, New Delhi, continuous submergence significantly improved DTPA-extractable Fe, Mn, Cu, but decreased Zn content in soil compared to irrigation at 1 or 3 DADPW at tillering and harvest stages of rice crop. An experiment carried out by Anurag (2006) [1] revealed that significantly higher N, P and K uptake was under irrigation scheduled at 3 day after disappearance of standing water than at 5 day after disappearance of standing water. Sarwar and Khanif (2005) [71] reported that different flooding regimes decreased Zn and Cu availability in soil, but their content in rice did not vary significantly, while continuous flooding (5 cm) throughout the crop cycle resulted in slightly lower content of these nutrients in rice straw compared to treatments involving 5 cm flooding for 3, 6 or 9 weeks followed by 1 cm flooding for rest of the period.

Belder *et al.* (2005) [9] reported that N recovery of rice under AWD was significantly lower (about 20%) than under conventional flooding (about 40%). Yang *et al.* (2004) [85] found that in the water regime of AWD, incorporation of organic manure significantly increased root length density, root weight, N, P and K uptake by rice plants and facilitated the allocation and transfer of nutrient elements, especially P to rice ears and grains. Bonkowski (2004) [12] reported that AWD increased the microbial biomass compared to flooded condition, which indicated that under aerobic soil condition, there would be larger population of soil fauna that contribute to biological processes for supplying N needs of plants. There is higher concentration and uptake of N and P under AWD and higher concentration and uptake of K in continuous flooding plots (Yang *et al*., 2003) [87]. Greater amount of N, P and K uptake by rice at higher irrigation levels was due to the fact that higher level of irrigation was more conductive for uptake of nutrients by the plants (Chaudhary, 2003). Rajesh and Thanunathan (2003) [61] observed more nutrient uptake under AWD irrigation system. Nutrient use efficiencies in flooded rice often low because of high losses, resulting in contamination of groundwater and high fertilizer costs for farmers.

Although the denitrification loss of N may increase under AWD practice but both the leaching and ammonia volatilization losses of N were reduced with AWD (Feng and Li, 2011) [26]. Wang *et al*. (2002) [84] indicated that AWD and N application practices had enormous scope for improving N use efficiency and yield of crop. Intermittent irrigation is believed to improve oxygen supply to rice root system with potential advantage for nutrient uptake (Stoop *et al*., 2002) [79]. AWD was one method of managing the water so that water would not be wasted but aid the root growth facilitating higher nutrient uptake and increase the land and water productivity (Sarkar, 2001). Continuous flooding has been proved to be detrimental to rice root growth as the free Fe^{2+} and S_2 were potentially toxic to rice plants as they can inhibit root growth and impair nutrient uptake (Sahrawat, 2000) [65]. Grigg *et al*. (2000) [32] found reduced N uptake from intermittent irrigation compared to flooding of rice and attributed partly to N losses from denitrification in AWD practice. Increased availability of nitrogen and phosphorus and the nitrogen could be utilized effectively leading to higher uptake in AWD conditions than the continuous flooding (Lu *et al*., 2000) [43].

7. Economics of rice under different irrigation regimes

Kishore (2016) [38] from Hyderabad reported that AWD irrigation regime of 5 cm submergence depth from 15 DAT to physiological maturity when the ponded water level drops to 5 or 10 cm below ground level in the field water tube (₹ 57,926 ha^{-1} and ₹ 56,468 ha^{-1}, respectively) registered higher net returns with a B:C ratio of 1.27 and 1.29, respectively. Sathish (2015) [72] concluded from a field experiment on sandy loam soils at Hyderabad that higher gross returns (₹ 83706 ha^{-1}) were obtained with recommended submergence of 2 - 5 cm water level and net returns (₹ 47245 ha^{-1}) and B:C (2.48) ratio were significantly higher with irrigation of 5 cm at 3 DADPW and irrigation of 5 cm when water falls tends below 5 cm from soil surface in field water tube (₹ 44986 ha^{-1}). Kumar *et al*. (2013) [41] revealed that maximum B:C ratio (1.35) was obtained under 7 cm irrigation at 1 DADPW while 1.11 and 1.07 B:C ratio was noticed with 7 cm irrigation at 3 and 5 DADPW, respectively.

Rahaman and Sinha (2013) [58] in West Bengal revealed that higher net returns (₹ 20281 ha^{-1}) and B:C ratio (1.78) was with saturation as compared to farmers practice and intermittent ponding (2 DAD 5 ± 0) from 15 to 35 DAT followed by continuous ponding. Application of irrigation when water level drops 15 cm below soil surface under AWD was found to be most profitable at Gaziapur, Bangladesh (Paul *et al*., 2013) [56]. Dass and Chandra (2012) [23] reported that irrigation at 1 and 3 DADSW recorded higher net returns than 5 DADSW due to higher grain and straw yields and the B:C ratio was the highest (1.09) with irrigation at 3 DADSW in sandy loam soils of *Tarai* region of India. Lampayan *et al*. (2009) [42] reported that the practice of AWD irrigation resulted in similar yield level as that of CF but saved 16 to 24 per cent of water cost and 20 to 25 per cent of production costs. Subramanyam *et al.* (2007) [80] stated that continuous flooding resulted in realising higher net returns (₹ 18,037 - 26,817 ha^{-1}) and B:C ratio (2.15 - 2.70) over other irrigation regimes but applying irrigation water at 1 DADPW was found at par with continuous flooding (CF).

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