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Review Article

Changes in Rice Physiology and Soil Conditions during Low-Water-Input Rice Production System - A Short Review

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ABSTRACT

Water wise rice production is now a primary concern that ensures saving of considerable amount of fresh water volume as well overcoming water shortage for rice production. Several potential types of research have revealed that low water input for rice cultivation increases the productivity of water and sustains the production of rice. Several other studies have also proven the effects of water levels on the yield and yield parameters of rice plants. However, it is still necessary to update current scientific findings on low water use rice production which is related with the changes of plant and soil parameters. To date, it has been established that low water use in rice cultivation does not affect rice yield and rice parameters but saves voluminous amount of fresh water and reduces greenhouse gas emission. This review demonstrates different aspects of water use for rice cultivation and offers current updates on the changes of plant parameters and soil chemical properties. Finally, this review confirms that reducing water input from a traditional practice to water-wise rice cultivation sustains rice production without affecting plant and soil parameters.

Keywords: Irrigation, light-related properties and yield, rice, sustainable rice production, physiological properties

INTRODUCTION

In Asia, rice provides approximately 32% of calorie uptake and uses 50% of freshwater used in rice farming (IRRI, 2001). However, water availability was seen to drop by 40 to 60% between 1955

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and 1990, and more decline of 15 to 54% was witnessed in the following several years (Gleick, 1993). The decreasing area of land cultivated with irrigated rice and shifting of diets from starch-based to meat and dairy products require greater amounts of fresh water, resulting in water scarcity (Hoekstra & Chapagain, 2008). According to Tuong and Bouman (2003), rice is very sensitive to water stress, therefore, low water input may threaten food security, resulting in reduction of rice yields (Cassman, Olk, & Doberman, 1997) and soil health (Jahan, 2004). Therefore, sustainable rice production is necessary under stress conditions to feed the rapidly growing world population. In this regard, yields of rice must be sustained with less water input to increase water productivity for irrigated rice system, particularly in Asia, where 50% of irrigation water is used for rice production (Barker, Dawe, Tuong, Bhuiyan, & Guerra, 1999). Consequently, an innovative system is needed to confirm that low water status of the soil will not affect rice production but improve rice ecosystem. Several recent reports have confirmed that low water use in rice cultivation does not affect rice yield, soil properties and plant physiological parameters (Jahan, 2004; Jahan, 2016; Jahan, Khanif, Sinniah, Nozulaidi, & Khairi, 2012; Khairi, Naqib, Nozulaidi, Hasan, & Jahan, 2017).

Traditional flooding irrigation in rice cultivation did not increase yield and yield parameters than that of low water use rice cultivation (Khairi, Nozulaidi, Afifah, & Jahan, 2015a; Khairi et al., 2017). In fact, it saturated to 1 cm flooding sustained rice production and saved a larger amount of fresh water compared to traditional flooding system. Water stress causes soil moisture deficit and affects the plant's height, tiller numbers (Jahan, Nozulaidi, Khairi, & Khanif, 2013a; Khairi, Nozulaidi, & Jahan, 2015b). Plants respond to stress conditions such as drought and salinity by changing the morphology and physiological parameters of rice plants (Khairi et al., 2015b; Nozulaidi, Khairi, & Jahan, 2015). Similarly, Jahan (2016) reported that rice has exhibited reduction of filled grains and increased unfilled grains due to water stress.

Flooded condition increases Fe(II) and Mn(II), which are controlled by the soil pH levels (Jahan, Khanif, & Sinniah, 2013b; Ponnamperuma, Attanandana, & Beye, 1973). The flooding soil has shown higher availability of phosphorus compared to the dry soil (Gupta, Ladha, Singh, Singh, & Pathak, 2007; Jahan, 2016), and flooding has been found to reduce oxygen concentration and cause anaerobiosis that declines redox potential (Eh) value to less than –150 mV where low water input shows relatively oxidised condition that increases Eh value of more than - 150 mV (Jahan & Khanif, 2005a). Instead, the availability of water in the soil improves the availability of nutrients to rice plants (Jahan, Khanif, Syed Omar, & Sinniah, 2004; Jahan et al., 2013a; Jahan & Khanif, 2005b, 2005c).

Water deficit disturbs leaf water potentials, gas exchange through opening of guard cells (Khairi et al., 2015a; 2017), which is closed under water stress (Jahan, Nozulaidi, Khandaker, Afifah, & Husna, 2014; 2016). Low water input reduces the relative water content of leaves, photosynthesis rate, transpiration rate and CO_2 movement (Khairi, Nozulaidi, & Jahan, 2016). Antioxidants, such as glutathione monoethyl ester, and N-acetyle cysteine which increase glutathione content in cells (Jahan, Nakamura, & Murata, 2011), have been found in several studies to reduce the detrimental effects of low nutrients and water stress on physiological, and light-related parameters of *arabidopsis* plants (Jahan et al., 2011, 2014, 2016), rice plants (Nozulaidi 2015; Khairi et al., 2015a) and corn plants (Inani, Nozulaidi, Khairi, Abdulkadir, & Jahan, 2015; Munirah, Jahan, & Nashriyah, 2015a; Munirah, Khairi, Nozulaidi, & Jahan, 2015b; Syuhada et al., 2014; Syuhada & Jahan, 2016). Therefore, it is important to focus on recent developments in the innovative use of water for sustainable rice production and justify the soil and plant parameters. This review cites new understanding of the low water use on plant and soil parameters for sustainable rice production.

Water Assessment for Agriculture

The global water scenarios were set by World Water Council during the preparation of World Water Vision. The increase in greenhouse gas concentrations in the atmosphere due to the burning of fossil fuels, deforestation, land-use changes, livestock and fertilisation has increased global average temperature (IPCC, 2008). Fresh water covers about three percent of the total global water resources and less than one percent of fresh water (less than 0.01% of total global water) is available on the earth's liquid surface (Mayers et al., 2009). Groundwater is a significant source of water, which is nearly half of the world's drinking water (WWAP, 2009) and also represents approximately 43% of all water used for irrigation (Siebert et al., 2010). Shiklomanov (1999) asserted that rapid population growth has resulted in withdrawals of water over the last 50 years (WWAP, 2009) from agriculture and industry, which may affect water-depended crop production.

According to the statistics by WEF (20110, irrigated agriculture uses about 70% of the total freshwater or approximately 3100 billion m^3 which is expected to increase to 4500 billion m^3 by 2030. Several food-importing countries have been buying or leasing land in developing countries to improve their food security and water security (Braun & Meinzen-Dick, 2009). Economic growth combined with increased individual wealth has led to a shift from starch-based diets to meat and dairy, which have had the greatest impact on water consumption over the past 30 years (FAO, 2006). This system requires eight to 10 times more water than cereal production (WWAP, 2009). Rainfed agriculture covers about 80% of agricultural land worldwide associated with low yield and high on-farm water losses (WWAP, 2009). Water productivity plays an important role in reducing the demand for agricultural water use (Molden et al., 2007). In urban agriculture, using wastewater for agriculture reduces fresh water requirements (Qadir et al., 2007). Water conservation techniques reduce fresh water use for crop production (DOE, 2002). Therefore, it is important that innovative information and communications technologies be settled for the sustainable management of water resources and use for rice production from where a larger amount of fresh water can be diverted to municipal purposes.

Changes of Physiological Parameters of Rice Plants under Water Conditions

Chlorophyll (Chl) content rules on light reaction in the reaction center of photosystem II and shows an imperative character on plant growth (Jahan et al., 2016). Deficient soil water emulates Chl content of leaf of rice plants (Khairi et al., 2015a), which may disturb photosynthesis rate (Munirah et al., 2015a; Inani et al., 2015) and reduction of CO_2 assimilation (Awal & Ikeda, 2002). This result shows consistent results with the study where Khairi et al. (2015a) confirmed accumulation of lower Chl content in leaves of rice plants to be due to low water and sustained similar effect on Chl fluorescences and quantum yield. Therefore, water levels at saturated to above do not affect Chl-controlled plant growth. Furthermore, Chl content is positively correlated with glutathione (GSH) content in plants (Jahan et al., 2016) and supports that low water might touch GSH content (Okuma et al., 2011). Besides, transpiration and stomatal conductance decline in leaves are endorsed by low water, which might increase abscisic acid-persuaded stomatal closure (Jahan et al., 2008; Okuma et al., 2011). There is positive relationship between reduction of Chl and GSH content to the stomatal aperture (Jahan et al., 2016). However, no effect of intracellular GSH is confirmed (Jahan et al., 2013a). Low water inputs reduce transpirational water loss through leaves of rice plants (Awal & Ikeda, 2002), tissue water potential (Kato et al., 2004) which suggest that cell water potential is essential for the growth of rice plants which might enhance nutrients' availability for roots (Khairi, Nozulaidi, Afifah, & Jahan, 2015a).

Low water input significantly reduces Chl parameters, that is, non-photochemical quenching (NPQ) in rice plants (Khairi et al., 2015a). In addition, Foyer and Harbinson (1999) also stated that NPQ regulates Chl parameters and protects light reaction in the pathway of photosynthetic electron (Bailey, Mann, Robinson, & Scanlan, 2005). Moreover, NPQ also shows positive relation to the photosynthesis in plants (Schubert, Andersson, & Snoeijs, 2006). Water level below than saturated condition significantly affects NPQ than flooding condition (Khairi et al., 2015a). These results relate to the fact that water stress disturbs light energy and NPQ in plants and finally reduces photosynthesis (Schubert et al., 2006) and glutathione biosynthesis (Jahan et al., 2016).

Several investigations have reported application of soil amendments (Chelah, Nordin, Musliania, Khanif, & Jahan, 2011), trace elements (Inani et al., 2015; Munirah et al., 2015a; Syuhada et al., 2014), low water input (Jahan et al., 2013a, 2013b; Khairi et al., 2015a), salinity (Nozulaidi et al., 2015), and antioxidant such as glutathione (Inani et al., 2015; Munirah et al., 2015b; Syuhada & Jahan, 2016) coordinate relative water content (RWC), plant growth, and light parameters in different plants. Low water irrigation controls RWC of leaf of rice plants (Khairi et al., 2017), photosynthesis rate (Kura-Hotta, Satoh, & Katoh, 1987), light-regulated RWC (Jahan et al., 2016), and salinity-induced plant growth (Nozulaidi et al., 2015). Furthermore, low water irrigation decreases photosynthesis rate, and transpiration rate to reduce carbon dioxide (CO_2) assimilation in plants during the process of photosynthesis (Awal & Ikeda, 2002). Therefore, it is possible that dry soil condition induces drought stress to the rice plants, which finally close the stoma (Jahan et al., 2008; Okuma et al., 2011) under which transpirational water loss (Awal & Ikeda, 2002), tissue water potential (Kato et al., 2004) to drop in production of rice (Khairi et al., 2015a) is seen. Consequently, irrigation of water for rice production in an innovative way is a scientific concern to sustain rice production in low water conditions.

Changes of Yield Parameters of Rice Plants under Water Conditions

Rice production is related to extensive water circumstances, soil categories and climates. Conventional flooding scheme needs a larger quantity of fresh water in rice cultivation (Jahan, 2016; Khairi et al., 2015a; Nozulaidi et al., 2015). Different water input affects the number of tillers and panicles of rice plants differently, including filled grains and yield of rice plants (Sariam, Khanif, & Zahrah, 2002). This effect of low water extends to vegetative growth, grain yield, root length and root weight of rice plants (Jahan, 2016; Khairi et al., 2015b; Nozulaidi et al., 2015) and nutritional accumulation in rice grains (Singh & Bhattacharyya, 1989). Saturated or above water level shows no effect on yield parameters of rice plants (Khairi et al., 2015a, 2015b; Tuong & Bouman, 2003). Water deficit reduces flowering and grain yield by 50% and 21%, respectively (Mahmood, David, & Legates, 2004; Pirdashti, Sarvestani, Nematzadeh, & Ismail, 2004). It is because of reduction of different physiological parameters such as transpirational function (Vandeleur et al., 2009), tissue water potential (Kato et al., 2004), chlorophyll content (Sheela & Alexander, 1996) and photosynthetic units and photosynthesis (Kura-Hotta et al., 1987) of rice plants.

Water stress also seriously affects anthesis and grain filling of rice plants and leads to spikelet degeneration, spikelet sterility and reduction in grain setting, increase in unfilled grain, and reduction of 1000-grain weight (Chen, 2004; Wu, Yongsheng, & Yan, 2011). In addition, alternative dry and wet soil conditions significantly affect rice yields due to the degree of water stress induced to the rice plants (Khairi et al., 2015a). In contrast, Sariam et al. (2002) found that saturated soil does not affect plant growth as well as yield of rice plants because of enough root growth. Saturated water conditions also do not affect tiller numbers, panicle numbers and grain production per plant (Jahan et al., 2004). Therefore, maintaining water level from saturated to above sustains the growth and yield parameters of rice plants.

Table 1
Major changes in rice physiology and yield under traditional water-stressed conditions and low-water-input irrigation system

Physiological/ yield parameter of rice	*Traditional water-stressed condition*	*Low-water-input irrigation*	*Inference*	*References*
Plant growth	Reduction of leaf development affected plant growth	No reduction of plant growth	Saturated to above water condition did not affect plant growth	Bouchabke et al. (2006); Khairi et al. (2015b); Welcker et al. (2007)
Tiller numbers / panicle numbers	Reduction against traditional flooding	Showed similar to the traditional flooding	Very sensitive to soil with dry condition	Centritto et al. (2009); Khairi et al. (2015a)
Grain yield	Filled grain decreased of but unfilled grains increased	Similar to the traditional flooding	Soil with dry condition reduced grain filling	Chen (2004); Mahmood et al. (2004); Pirdashti et al. (2004); Sariam et al. (2002); Tuong & Bouman (2003); Wu et al. (2011)
Leaf and tissue water content	Leaves show wilting symptom	No symptom is observed	Soil with saturated condition is important	Boonjung & Fukai (1996); Kato et al. (2004); Khairi et al. (2015); Nunes et al. (2008); Wang et al. (2010)
Photosynthesis rate / transpiration rate / CO_2 movement	Loss of functional unit of photosynthesis that affects CO_2 assimilation and transpiration	Gas exchange shows normal to the traditional flooding	Loss of ATP synthesis affects photosynthesis rate under water stress condition	Awal & Ikeda (2002); Kura-Hotta et al. (1987); Tezara et al. (1999); Vandeleur et al. (2009)
Chlorophyll content	Leaf shows yellowish colour due to nutrient unavailability	Chl content shows similar to the traditional flooding	Reduction of Chl *a*	Chaum et al. (2010); Sheela & Alexander (1996)
Stomatal aperture	Decline stomatal aperture to affect gas movement	No effect on water loss and stomatal aperture	Disturb balance between respiration and photosynthesis	Jahan et al. (2008); Joseph et al. (2014); Okuma et al. (2011)
Non-photochemical quenching	Affects photosynthetic photon flux density	Maintain maximum Chl fluorescence value	Protects light reaction in the pathway of photosynthetic electron	Bailey et al. (2005); Foyer & Harbinson (1999); Flexas et al. (2002); Schubert et al. (2006)

Changes of Phytoavailability of Plants' Nutrients under Water Conditions

Soil water condition changes the properties of soil including phytoavailability of nutrients, radical oxygen transport and ionic balancing (Laskov, Horn, & Hupfer, 2006). Flooding water condenses oxygen source in the soil, which disturbs various anaerobic microorganisms and finally change the oxidised condition to reduced condition (Ponnamperuma, 1972). Nevertheless, oxygen must be contacted in roots, otherwise, it may lead to lacking of root energy (Drew, 1990). A reduced condition of soil shakes different processes of submerged soil including chemical and biological functions (Gambrell & Patrick, 1978). More nutrients dissolve in water during high flooding, most of which, are lost from soil through leaching (Tsheboeng, Bonyongo, & Murray-Hudson, 2014). Flooding condition displaces oxygen which declines organic matter decomposition and results in low nutrients in soil (Gallardo, 2003).

Irrigated rice uses portion of applied nitrogen (N) fertiliser in which substantial quantities of applied N are misplaced by leaching, denitrification, and volatilisation (Blair, Faulkner, Till, & Poulton, 2006; Zhao, Wu, Dong, & Li 2010). Nitrogen use efficiency in flooded soil is only about 30 to 35% and about 50% of applied N is lost through different N transformation processes (Zhao et al., 2010). Nutrient phytoavailability in non-flooded soils is relatively distinct from the flooded soil. In flooded soil, nitrate is rapidly denitrified (Ponnamperuma, 1972) and NH_4-N would be the largest source of N nutrient for plants (Godshalk & Wetzel, 1978). Rice plants accumulate significant amount of N at the vegetative stage than that of later stage including ripening stage (Jahan, 2016).

Phosphorus (P) phytoavailability rises in submerged soil encompasses the reduction of ferric to ferrous phosphate while $AlPO_4$ hydrolysis and $FePO_4$ reduction are important (Patrick & Mahapatra, 1968). Flooding condition induces P availability after the soil is flooded (Jahan et al., 2004; Khairi et al., 2017). Flooding at prolonged period enhanced the fixation rate of P in soil through increasing P affinity to clay structure and pH dependency (Gallardo, 2003; Mitsch & Gosselink, 2000; Patrick & Mahapatra, 1968). Anoxic condition due to prolonged flooding increases P mobilisation in soil (Gallardo, 2003; Mitsch and Gosselink, 2000). Potassium is displaced by Fe^{2+} and NH_4^+ from the colloidal exchange sites of the soil in the flooded soil (Ponnamperuma, 1972). This result leads to availability of the K concentration in the flooded soil by decreasing the fixation rate. Olk, Cassmon and Carlson (1995) stated that available K dropped after the flooding and decreased gradually with increasing growth of plants (Jahan, 2004; Khairi et al., 2017). Low flooding depth increases K content at the root zone (Tsheboeng et al., 2014) while high flooding reduces the K content due to leaching and dilution (Conklin, 2005). This result suggests that flooding increases solubility of potassium.

Availability of Fe^{2+} increases in flooded soil due to the fact that hydrated Fe^{3+} is reduced to Fe^{2+} (Ponnamperuma, 1972; Yoshida, 1981). In the flooded paddy soil, reducing phases trigger redox depletion of iron (Charlet, Markelova, Parsons, Couture, & Madé, 2013). The availability of Zn in the flooded soil increases under different flooding conditions (Jahan, 2016), and flooding also increases micronutrient solubility (Green, Heil, Cardon, Butters, & Kelly, 2003) and mass flow of Fe and Mn into roots. In contrast, prolonged flooding increases movement of micronutrients towards the subsoil. Thus, submergence causes the movement and precipitation of Fe or Mn in paddy soil development (Greipsson, 1996). This process may deplete nutrients from the topsoil through the reactions of adsorption-desorption or processes of precipitation-dissolution (Adriano, Wenzel, Vangronsveld, & Bolan, 2004). Periodical changes of flooding condition cause a variation in availability of nutrients to plants (Sebastian & Prasad, 2015) and contribute to mobilisation of micronutrients in the soil (Jahan, 2004; Jahan & Khanif, 2005c). Taken together, the above discussion indicates that low water use increases micronutrients in flooded soil for rice plants and sustained rice production (Jahan et al., 2016). Nevertheless, continuous flooding stimulates methane emission, a greenhouse gas, due to organic matter decomposition in anaerobic condition. Emissions of CH_4 and nitrous oxide are intensely linked to soil oxidation status (Hou, Chen, Wang, Van Cleemput, & Patrick, 2000).

Changes of Soil Redox State under Water Conditions

Depletion of oxygen in rice soils differs due to the different physical and chemical properties of soil which undergo reduction reactions that result in a drop in redox potential (Scharpenseel, Pfeiffer, & Becker-Heidmann, 1996). Reducing condition of the paddy soil causes a redox depletion of nutrients such as iron (Fe) and manganese (Mn) (Charlet, et al., 2013). In rice soils, water conditions affect redox potential (Eh) values (Jahan, 2004) that can contribute to environmental factors as well as to the territorial population (Pennington & Walters, 2006). Flooded water elevates enzyme activity such as alcohol dehydrogenase in numerous plants (Crawford, 1992) linked to anaerobic respiration. Root and rhizomes attain oxygen, which permit plants to maintain respiration and oxidisation and create oxygen gradient in soil redox state (Youssef & Saenger, 1998). This result is consistent with the previous study that low water level increases redox states in rice soil (Jahan & Khanif, 2005a). Increasing flooding level and time reduces redox value lower than 150 mV (Jahan, 2004) under which methane (CH_4) is produced and can affect the environment. The production of methane is one of the environmental constraints that significantly increase climate change factors (Kludze & DeLaune, 1995). However, when the water level is saturated to 1 cm flooding, the redox value increases to more than -100 mV (Jahan & Khanif, 2005a). This condition may prevent methane production. Soil reduction raises the requirement of the roots for oxygen (DeLaune, Pezeshki, & Pardue, 1990). In this condition, redox reaction and microbial activities release oxygen to the root rhizosphere (Laskov et al., 2006).

Therefore, there is possibility that redox potential (Eh) values in flooded rice soils probably influence plant growth by modifying oxygen transportation, and physiological variations (Kludze & DeLaune, 1995). However, flooding condition also increases phyto availability of nutrients concentrations for plant uptakes (Jahan, 2004). Sometimes, prolonged period of flooding makes nutrient concentration to a level that is not always good for plants, such as zinc (Pavanasasivam & Axley , 1980) and ferric and manganic forms (Ponnamperuma, 1972), Mn and Fe in tissues (Gries, Kappen, & Losch, 1990).

Table 2
Major changes in soil properties under traditional water-stressed conditions and low-water-input irrigation system

Soil properties	*Traditional water-stressed condition*	*Low-water-input irrigation*	*Inference*	*References*
Radical oxygen transport	Lacking of root energy to disturb redox balance	Microbial activities release oxygen	Soil to be in saturated condition	Drew (1990); Laskov et al. (2006)
Ionic balancing	Disturb the reactions of adsorption-desorption	Maintain precipitation-dissolution reaction	Minimum flooding water is necessary	Adriano et al. (2004); Gallardo (2003); Laskov et al. (2006)
Nutrients accumulation	Organic matter decomposition declined to result in low soil nutrients	Variation in availability of nutrients based on reaction condition	Saturated to flooding condition sustains nutrients	Singh and Bhattacharyya, 1989), Tsheboeng et al. (2014)
Macronutrients / Micronutrients	Affect movement of nutrients and pants unable to absorb.	Sufficient movement and phytoavailability of nutrients	Most nutrients are available for plants in the condition of saturated to above soil water condition	Blair et al. (2006); Charlet, et al. (2013); Gallardo (2003); Greipsson (1996); Gries et al. (1990); Mitsch & Gosselink (2000); Olk et al. (1995); Patrick & Mahapatra (1968); Pavanasasivam & Axley (1980); Ponnamperuma (1972); Yoshida (1981) Zhao et al. (2010)
Redox balance / Gas emission	Redox reaction disturb microbial activity to release nutrients for plants	Redox reaction release oxygen to the root rhizosphere	Reduction in emission of greenhouse gas under low-water-input	Hou et al. (2000); Jahan (2004); Jahan & Khanif (2005a); Laskov et al. (2006); Ponnamperuma (1972); Scharpenseel et al. (1996)

CONCLUSION

The recent advancement of water productivity in rice cultivation provides a new opportunity for the yield potential under low water conditions. The intention is to minimise water scarcity on rice production through low water input rice cultivation. Therefore, the influence of low water use in rice cultivation increases water sustainability to be diverted for other purposes. The progress in physiological functions of rice plants under drought stress may be caused by the discovery of genes motivating the complex physiological and biochemical aspects of rice plants. Therefore, giant investments in genomic analysis of rice plants is important to develop molecular markers for the capacity of the plant to osmotically regulate water stress. For example, the combination of the C_4 photosynthetic pathway into C_3 could be a conceivable upsurge to water productivity of rice plants and sustain rice production under low water condition without affecting the physiology, yield and soil parameters. Furthermore, hormonal signaling to the rice plants needs to be investigated to find out the relation between water levels and nutrient mobilisation in rice plants.

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