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Review Paper

Aerobic Rice and its significant perspective for sustainable crop production

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ABSTRACT

Aerobic rice (*Oryza sativa* L.) flourishes well under dry situations and caters a favourable option to solve the emerging water crisis in agricultural production. Water scarcity is touted as a grave concern in various rice-growing areas of the world, leading to introduction of water-saving aerobic rice, which is direct-seeded in non-puddled, non-flooded aerobic soil. This escalating dearth of water resources has drifted to the development and adoption of an aerobic rice system, which saves water input and improves water productivity by decreasing water use during the land preparation and minimizing seepage, percolation and evaporation losses. Inadequate water accessibility is a main restraint for the husbandry of rice in the conventional flooded systems, mainly in the semiarid regions of the world. Aerobic rice-cultivation caters a feasible alternative to traditional rice production system, permitting substantial water reserves, as rice systems is facing the challenge of giving higher yields with less water. This balance between water savings and grain yield ensues since the removal of irrigation causes water stress-induced alterations in the physical and biological root traits of the crop. Improved water productivity and decreased labour necessity are witnessed in the aerobic rice-production system, as the aerobic rice can cut up to 50% of irrigation water in contrast to lowland rice. Aerobic rice is acclaimed as a sustainable rice-production system for the future to manage water scarcity in the façade of anomalous and unpredictable rainfall.

Key words: Aerobic rice, GHGs, Profitability, Sustainable crop productivity, Soil health

INTRODUCTION

The global water crisis jeopardizes the sustainability of irrigated rice production in many rice-growing countries like China, India, Indonesia, Bangladesh, Vietnam, Thailand, and Philippines. According to Bouman *et al*. (2002), 15 million ha irrigated rice- growing areas of Asia may meet Physical water scarcity and 22 million ha may face Economic water scarcity. Due to the increasing global population and improvement in the quality of life, approximately 50% more food will be required by 2030, which will be doubled by 2050 (Banwart, 2011). To overcome such a situation, ways must be found to reduce water requirements and increase productivity of rice. Basically diverse methodology to lessen water inputs in rice is to cultivate the crop similar to irrigated upland crop like wheat (*Tritium aestivum* L.) or maize (*Zea mays* L.). Since upland such is cultivated in non-puddled, non-saturated 'aerobic' soil deprived of stagnant water. Irrigation is done to avail the soil water content in the root zone up to field capacity subsequently once it has touched a definite lower threshold level, such as intermediate amid field capacity and wilting point (Geethalakshmi *et al*., 2009).

Rice is the most vital staple food crop grown globally for nearly half of the world populace, especially for those in developing countries. In Assam (now Asom)-Meghalaya areas of India and in the mountain regions of southeast Asia and southwest China, rice was domesticated more than 7000 years ago (Swaminatham, 1984). It is the staple food for the 170 million people of the country and is grown on around 10.5 million ha (Islam *et al*., 2019). The global annual production of rice is about 496.40 million tonnes from 162.06 million ha of land in 2019–20 (Urmi *et al*., 2022).

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On average 35% of total calorie intake comes from rice in Asia (Baishya *et al*., 2016). Rice systems will supply low-priced carbohydrates for an exploding world population in the coming decades (Maclean *et al.,* 2013). To satisfy the world demand, rice production must be enhanced by 15% by 2050 (Sharkey *et al.,* 2016); requiring a rise in productivity on current cropland as well as feasibly extending to new zones befitting for rice. In spite of the prospective for intensification in production in regions such as South America and West Africa, the unavailability of irrigation water is frequently the major limitation (Balasubramanian *et al.,* 2007). Though irrigation water is highly available, there is increasing pressure to enhance water productivity in some regions. Aerobic rice is a novel term given by the International Rice Research Institute (IRRI), for high-yielding rice grown under non-flooded situations in non-puddled and unsaturated (aerobic) soil, which responds to nutrient supply, can be rainfed or irrigated, and withstands (occasional) flooding (Prasad, 2011). Farmers in Brazil, China, and other Asian countries have developed and adopted this system (Sarangi *et al*., 2017). It responds to high inputs, can be rainfed or irrigated, and withstands intermittent flooding. Aerobic rice is cultivated as an upland crop (unsaturated condition) with sufficient input and provision of irrigation when needed (Yadav *et al*., 2017). The soil is therefore aerobic or with availability of oxygen throughout the growing season, as compared to anaerobic traditional flooded fields. This idea is chiefly attempted for irrigated lowlands, where water is not adequate for rice cultivation and suitable uplands, where facilities for irrigation are available when needed (Belder *et al.,* 2005). Various techniques have been developed to decrease water consumption in rice cultivation, such as saturated soil culture on raised beds (Yadav *et al.,* 2011), alternate wetting and drying (Kadiyala *et al.,* 2012), system of rice intensification (Singh *et al.,* 2016) and aerobic rice cultivation (Chauhan *et al.,* 2011). Out of these, aerobic rice is found to be one of the most promising approaches in terms of water saving (Yadav *et al*, 2017). The recent concept of aerobic rice necessitates the exploitation of nutrient-responsive cultivars that are suited to aerobic soils (Prasad, 2011), aiming at production of 70–80% of high-input flooded rice. Aerobically developed rice may be an alternative to farmers wherein water is too scarce or costly to cultivate flooded rice, and in rainfed areas where rainfall is inadequate for the cultivation of flooded rice but adequate for upland crops (Bouman *et al.,* 2005).

Rationale for aerobic rice cultivation

- The key advantage is a cutback in water, ranging from 50 to 60% less in aerobic rice system (ARS) as compared to transplanted puddled rice (TPR). By lowering the water usage in field preparation and reducing seepage, percolation, and evaporation, aerobic rice revealed about 51% decrease in overall water usage and 32–88% progressive water productivity, expressed as gram of grain per kilogram of water, than flooded rice (Bouman *et al.,* 2005).
- It is inexpensive, as the labour necessity is reduced in comparison to flooded rice and can be mechanized (Belder *et al.,* 2005). On the other hand, flooded rice is labour- intensive for land preparation such as puddling, transplanting, and irrigation works in flooded rice (Das *et al*., 2015).
- Less emission of greenhouse gases from rice field (Naresh *et al.,* 2014).

Basic principles of aerobic rice system

- 'Aerobic rice' cultivation is a method, which requires specific protocols of practices for seed treatment, plant, soil, weed, water and nutrient management. The basic outlines of this system are:
- Direct sowing of treated seed in non-puddled field
- Existence of rainfed or fully irrigated or supplementary irrigated field
- Retaining water at below field capacity level and keeping soils aerated during the growing period
- Efficient monitoring for judicious weed control in suppressing weed growth
- Row to row spacing should be maintained at 20 or 25 cm with continuous sowing (Yadav *et al.,* 2017).
- Managing nutrients with organic inputs, viz. farmyard manure/compost/ vermicompost/ biofertilizers.
- Selection of suitable cultivars adapted in aerobic soils having higher yield potential than upland cultivars (Sridhara *et al.,* 2012; Sandhu *et al*., 2019).

Development in India

The effort on evolving varieties suited for ARS was initiated lately and is usually confined to screening available varieties. The ICAR-Indian Agricultural Research Institute (IARI), New Delhi, 'APO', 'IR 55419-04', 'IR 7437-46-1-1' (IRRI varieties), 'Pusa 834', 'Pusa RH 10' (IARI varieties), and 'Pro-Agro 6111' (a commercial variety) yielded above 4 t/ha under aerobic conditions. The water productivity of these varieties fluctuated between 0.42 and 0.47 kg/m^3 with irrigation at 20 kPa soil moisture potential (SMP), and between 0.50 and 0.55 kg/m^3, at 40 kPa SMP (Singh and Chinnusamy, 2007). The ICAR-National Rice Research Institute, Cuttack, Odisha, has developed rice varieties, suitable for aerobic rice cultivation, viz. 'Pyari' (4.0 t/ha), 'CR Dhan 201' (3.8 t/ha), 'CR Dhan 202' (3.7 t/ha), 'Sachala' (4.0 t/ha), 'CR Dhan 205' (4.2 t/ha) and 'CR Dhan 206' (4.2 t/ha) which gave higher average yield than upland high gave varieties. The first drought-tolerant aerobic rice variety 'MAS 946-1' was developed in 2007 by the University of Agricultural Science (UAS), Bengaluru, Karnataka. Few other varieties such as 'PMK 3', 'MAS 25' and 'MAS 26' have also been developed by conventional breeding and marker-assisted selection techniques for aerobic cultivation (Hittalmani, 2009).

Viability of adoption

Aerobic rice can be viable in the following areas:

- Upland areas and mid-upland where land is flat. Deep soils, can provide water to the crop between rainfall events/ irrigation (Maiti and Banerjee, 2011).
- Irrigated areas with very scanty water or costly that lowland rice cannot be sustained any longer in higher slopes or terraces in undulating areas.
- Rainfed zones where precipitation is not enough to permit lowland rice cultivation, but ample for aerobic rice.
- Suitable upland regions wherein supplementary irrigation is accessible or rainfed areas where unrestrained flooding and waterlogging affected by substantial rainfall and brimming rivers averting the adoption of upland crops (Patel *et al*., 2010; Chongtham *et al.,* 2016; Lokesh and Basavaraja, 2019).

A main element of achievement in the aerobic rice system is choice of suitable cultivars (Nie *et al.,* 2012). Only limited successful aerobic rice cultivars with high-yield potential and wide tolerant to biotic and abiotic stresses are presently available for commercially cultivation.

Water requirement and water productivity

The development of ARS technology began in China during 1980s for breeding high-yielding rice varieties cultivated in non-puddled, non-flooded aerobic soil. In 2001, the International Rice Research Institute (IRRI) initiated collaboration with other institutes like the China Agricultural University, the National Irrigation Administration in Tarlac, and the Philippine Rice Research Institute to research on the appropriate crop-water-nutrient-management recommendations for this system (Templeton and Bayot, 2011). The crop calendar for the cultivation of aerobic rice is depicted in Fig. 1. The varieties of this aerobic rice have the features of upland varieties developed on non-flooded sloping islands and lowland varieties cultivated in irrigated, flooded fields. In this technology, rice seeds are sown directly in well-tilled and levelled fields with uniform slope devoid of puddling to create aerobic condition during the course of the crop season. The conventional transplanting technique of rice used higher amount of water (16,200 m^3/ha) while aerobic rice used the least quantity (9,687 m^3/ha) and resulted in a water saving of 32.9–43.9% over transplanted rice (Geethalakshmi *et al.,* 2009). According to Sudhir *et al.* (2011), water requirement was high in flooded rice 1,473 mm in contrast to aerobic rice 940 mm.

Aerobic rice production system excludes incessant seepage and percolation losses, reduction in evaporation, as there is total non-existence of impounding water at any point of time in the field (Chauhan *et al.,* 2015). Besides, this system enables efficient use of precipitation and thus improves water productivity (Bhuyan *et al.,* 2012). A valuation of water requisite of lowland flooded rice and aerobic rice system specifies that, aerobic rice system can save about 45% of water (Lampayan *et al.,* 2010). Aerobic rice production minimizes the water use by reducing incessant seepage, percolation and by lessening evaporation (Lampayan and Bouman*,* 2005). Flooded rice required more irrigation water (358 mm) than aerobic rice (89 mm) for land preparation and doubled during the crop stand (1,148 and 481 mm). In ARS, incessant leaching, percola-

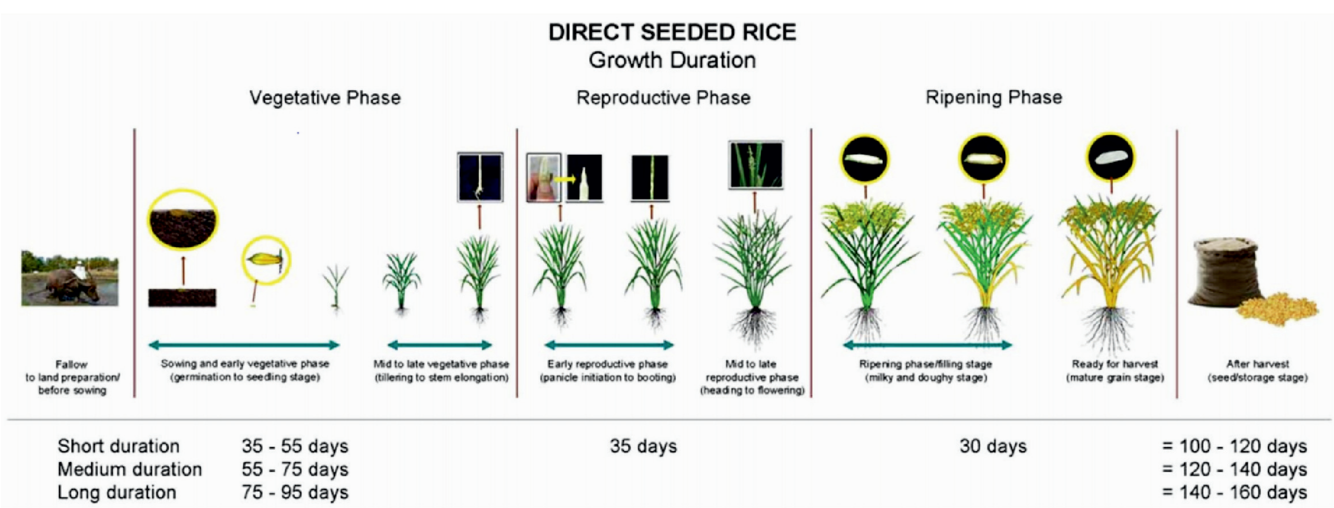

Fig. 1. Crop calendar of direct-seeded aerobic rice. (*Source:* Rice Knowledge bank IRRI)

tion and evaporation losses are widely decreased; it proficiently exploits the precipitation and improves the water efficiency (Bouman *et al.,* 2005).

Nutrient management

At the time of land preparation, thoroughly mix well-decomposed cowdung manure/ FYM/ compost @ 5 t/ha in the soil. If, Zn is deficient in soil, apply $ZnSO_4$ @ 20–25 kg/ha. For proper soil-health management, apply of N, P_2O_5, K_2O @ 100–125, 60–40, 60–40 kg/ha. Apply half dose of N, full dose of P_2O_5, 75% K_2O and full dose of Zn (20–25 kg $ZnSO_4$/ha) as basal and remaining dose of N in 2 splits (25% N at active tillering and 25% N along with 25% K at time of land preparation at panicle initiation) are applied. Integration of both inorganic and organic sources for nutrient supplementation proves to better the growth and yield of aerobic rice (Jana *et al*., 2020). Jana (2012) recommended the inclusion of *Gliricidia* as greenmanure @ 3 t/ha, at 20 days before sowing in aerobic rice. Taketsaba *et al.* (2018) reported promising results in aerobic rice production owing to the inclusion of biofertilizers along with inorganic fertilizers. Substitution of a certain portion of recommended dose of fertilizer (RDF) by organic nutrient sources like vermicompost/ FYM/ greenmanure/ biofertilizers aids in regulated release and continuous supply of nutrients in balance quantity throughout various growth stages of rice plants, thus facilitating better photosynthesis and assimilation of photosynthates, higher rate of dry-matter accumulation, and subsequently improves yield attributes (panicles with more number of fertile grains and higher test weight), the yield of aerobic rice (Kumar *et al*., 2012; Das *et al*., 2014; Singh *et al*., 2018; Jana *et al*., 2020). There are certain reports of aerobic rice responding well to precision nutrient-management technique like drip fertigation. Application of 25% N and K from sowing to 30 days after sowing (DAS) + 25% from 31 to 50 DAS + 25% from 51 to 80 DAS + 25% from 81 to 105 DAS through drip irrigation resulted in significantly higher grain yield over soil application of N and K (Nagaraju *et al*., 2016). Singh *et al*. (2017) observed a significant increment in yield, content, and uptake of primary and secondary nutrients of aerobic rice at the application of 125% N, P, and K of RDF through drip fertigation.

Plant growth and yield

Rice has been cultivated under non-flooded, aerobic soil conditions in uplands for many years, wherein yields are meagre (1–2 t/ha), due to adverse ecological situations, minimum use of external inputs, and low yield potential of upland rice cultivars. In the Philippines, the wet-season crop yields were 4 to more than 5 t/ha while in the dry season the crop yields ranged from more than 6 t/ha to total yield failure. The yields that can be achieved ranged from 4.5 to 6.5 t/ha (Sinclair, 2018). An upland rice variety ‘PMK 3’ gave the highest grain yield of (3,688 kg/ha) and it was significantly better than other rice varieties under aerobic rice cultivation in Coimbatore, Tamil Nadu (Shaygany *et al*., 2012). The highest grain yield (4.15 and 4.36 t/ha) was attained by ‘IET-17509’ and acceptable grain yield (2.98 and 3.23 t/ha) was recorded from ‘Annada’ in aerobic rice system under unpuddled situation during the winter (*rabi*) season of 2011 at Rice Research Station, Bankura, West Bengal. Yield decline as related to traditional system is the noticeable factor inhibits the cultivation of aerobic rice. Patel *et al.* (2010) reported that, the yield difference between aerobic (average yield, 1.67 Mg/ha) and flooded rice (average yield, 2.31 Mg/ha) ranged from 18.4 to 37.8%. Bouman *et al.* (2005) stated that, the mean yield was 32% lower under aerobic conditions than under flooded conditions. Ghosh *et al.* (2012) observed 12% decline in yield of aerobic rice when compared to incessant submergence. Yield decline of monocropped aerobic rice is a limitation to the extensive adoption of aerobic rice technology. The crop advancement and yield decline of monocropped aerobic rice are supposed to be affected by soil sickness (Goswami, 2010). Soil sickness comprises of biotic factors, such as nematodes and soil-borne pathogens, and abiotic factors, such as variations in soil-nutrient accessibility and toxic materials from root dregs (De Waele *et al.,* 2013; Galeng *et al.,* 2018). The extent of yield degeneration postincessant cropping of aerobic rice relies on the quantum of seasons where aerobic rice was unceasingly cropped, soil properties, climates rice cultivars, and management practices (Habimana *et al.,* 2019). In general, the yield difference between aerobic and flooded rice ranged from 8 to 69% depending on the number of seasons that aerobic rice has been continuously grown (Haque *et al.,* 2016). The yield gap between aerobic and flooded rice widened as the number of cropping seasons increased. Peng *et al.* (2006) reported the highest yield gap in the seventh term when the changeamongst the aerobic rice and flooded rice reached 69% in ‘Apo’ variety.

Effect on soil properties

It was revealed that, a decrease in soil organic matter as one of the feasible cause for a reduction in yield in aerobic cultivation, since total soil nitrogen at physiological maturity in the micro plots was not appreciably low in aerobic than the soil that remained in continuous flooded situation both in 2002 and 2003 (Peng *et al.,* 2006). As soil-extractable NO_3^+, NH_4^+ do not account beyond 0.2% of total nitrogen at physiological maturity; more or less all nitrogen was in organic form. As Liu *et al*. (2017) assumed that the C: N ratio between flooded and aerobic soils show no variation, they concluded that soil organic matter content did not vary between the 2 moisture regimes after the 2 seasons. They forecasted a reduction in soil organic matter in aerobic system in comparison to permanent flooding or the rotational flooded rice-aerobic rice. In this context, integrated nutrient management can be of great help to resolve this issue, as it emphasizes the inclusion of organic inputs like FYM, vermicompost, and other animal/ plant sources along with inorganic nutrient sources. Integrated nutrient-management (INM) acts as a source of energy, organic carbon and available nitrogen for the growth of soil microbes and improvement of physical properties of soil, and also has a great residual effect on subsequent crops (Selim, 2020). Many researchers have observed that, substitution of RDF up to 50% by organic sources resulted in marked improvement in yield as well in soil physico-chemical and biological properties (Pandey *et al*., 2007; Jana *et al*., 2020).

Effect on nutrient status in soil

In the case of upland rice cultivation, it was reported that inadequate water supply is the major limitation to productivity, followed by nitrogen when moisture is adequate (Nie *et al*., 2008). The transition from the flooded condition to aerobic condition influences soil *p*H the master soil variable–that influences myriads of soil biological, chemical and physical properties and processes including soil-nutrient dynamics that affect plant growth and biomass yield (Neina, 2019). An increase in soil *p*H after continuous aerobic rice monocropping appeared to be the main reason for yield decline/ failure (Nie *et al*., 2012). Several researchers opined that, deficiency of nutrients like nitrogen (Mahajan *et al*., 2011) and micronutrients (Kreye *et al*., 2009) are associated with yield failure under continuous aerobic rice cropping. Furthermore, nutrient uptake and distribution to plants may be limited as a result of poor release rates to roots through mass flow and diffusion because both of these phenomena are affected by the decreased soil-moisture content. At the same time, reduced uptake of essential elements other than nitrogen may also be a limitation for rice in aerobic soils. Kreye *et al*. (2009) recorded that in the case of soil in a flooding situation, most of the essential nutrients are normally more accessible, except for sulphur, zinc, copper and phosphorus, accessibility of iron and manganese are mainly high in anaerobic soils because of low redox potential. On the other hand under aerobic soils, iron and manganese might be inhibiting, particularly when the soil is alkaline. Nitrogen-management practices played important roles in the continuous aerobic rice cropping system. It was reported that, N application significantly alleviated the continuous cropping obstacle of aerobic rice (Nie *et al.,* 2008). Further research showed that different N forms had different effects on plant growth of rice plants grown aerobically in the soil with a monocropping history of aerobic rice (Nie *et al*., 2009). Among N forms, ammonium sulfate was the most effective in alleviating the growth inhibition of continuous aerobic rice (Nie *et al*., 2009). An increase in soil *p*H associated with continuous cropping of aerobic rice could be mitigated by using the right source of N fertilizer (e.g. ammonium sulphate).

Physiological changes under water stress

Drought is clearly one of the major ecological constraints, restricting the production and yield of crops. Rice is regarded as a drought-susceptible crop species, though, among thesespecies; there is lots of varietal difference in sensitivity to drought. Under aerobic situation, rice crop might encounter moisture stress. Drought stress reduces the rate of photosynthesis (Okonji *et al.,* 2012). Extreme drought stress also restricts the photosynthetic rate of plants via altering the content and disturbing the component of chlorophyll and ruining the photosynthetic apparatus (Challagulla *et al.,* 2015). Plants to some extent may defend themselves from mild drought stress by producing various osmoprotectants, amongst which proline is considered to be the widely synthesized compatible osmolytes in plants under drought stress. The aggregation of proline could as well be noticed in case of other stresses, viz. elevated temperature, salinity and starvation of nutrients like phosphates (Aleksza *et al*., 2017). Coelho *et al.* (2006) reported that, proline do not hamper the other physico-biochemical processes and enable the plants to cope with various stresses. The build-up of proline in plant is also an obvious indicator for ecological stresses, mainly in crops under moisture stress (Das, 2014).

Green house gas emission: Low methane production

From ecological view point aerobic rice production process is relatively moreenvironmental-friendly method and safer than the traditional rice farming. The process of methanogenesis, that is the release of methane through breakdown of organic matter, is restricted as soil bacteria disintegrate the organic matter in presence of oxygen. Methane is synthesized via anaerobic disintegration of organic matter in the soil generally in traditional rice-farming method. Templeton and Bayot (2011) reported that, about 50% decrease in CH_4 production in aerobic rice system from trials carried out at the International Rice Research Institute (IRRI). Therefore, it can be said that the aerobic rice cultivation process is an environment friendly method and safer for the biosphere. Shashidhar (2008) stated that, aerobic rice will help reduce both methane and nitrous oxide production rate from paddy farms with no effects on the productivity. Methane flux was approximately 10 times more obvious in persistently flooded situation than in continually non-flooded environment. Jat *et al*. (2008) reported a considerably low afflux of methane under aerobic situation (3.03 mg/m^2/h) in comparison to flooded rice situation (6.16 mg/m^2/h).

Economics

Normally the cultivation cost involved in the traditional method of rice cultivation was more than the aerobic system because of additional inputs required for the preparation and raising of nursery and for transplanting process (Sharma *et al*., 2016). Aerobic rice technique reduces labour needs, input requirements, investment and saves time by timely sowing of rice and reduces crop duration by 7–10 days than transplanted rice (Sujan *et al*., 2017). Nevertheless, gross income as well as benefit: cost ratio were more in case of flooded rice; in advantageous situation with proper cultural operations; the gross returns and benefit: cost ratio could be enhanced significantly for aerobic rice (Kadiyala *et al.,* 2012). Several workers reported that, the gross return of rice under non-puddled condition, i.e. under strip tillage and bed formed was than compared to transplanting under puddle condition (Haque *et al*., 2016; Singh *et al*., 2017). Sarangi *et al.* (2017) noticed that , the net returns and benefit: cost ratio of direct-seeded rice were higher than non-puddled transplanted rice, however there was non-significant difference between them in terms of gross returns. Rana *et al.* (2014) while analyzing the economical data reported that, direct-seeded rice showed higher net returns and benefit: cost ratio over transplanted rice owing to high yield and lower labour charges. Additionally, in current situations cost of energy for only drawing water was kept into account for obtaining irrigation charge. Though, in the future, if water is priced, even at a minimal cost, the cost of growing rice using traditional approach will be significantly high (Priyanka *et al*., 2012).

Sustainability of aerobic rice system

Peng *et al.,* (2006) reported that under aerobic rice cultivation at the International Rice Research Institute (IRRI), productions of aerobic rice were gradually reduced in due course in comparison to the traditional system (control). In India, sufficient information is available from experiments where rice was cultivated on raised beds (Bhuyan *et al*., 2012; Naresh *et al*., 2014; Chongtham *et al*., 2016). Singh *et al.* (2005) reported that, at Modipuram, the comparative yield of TPR on permanent beds decreased considerably over the years, from 90% of permanent transplanted rice (PTR) in the first crop to 77% of PTR in the third rice crop. Jat *et al.* (2008) also recorded that the production of fourth crop of DSR on permanent beds was only 76% of PTR. Likewise, under on-farm trials in Punjab, the production of rice on raised beds was almost 50% of that in PTR and the productivity of both transplanted or DSR on beds reduced considerably by the third rice crop (Kukal *et al.,* 2008). Information on reduction in yield and even failure in continuous upland rice farming is available in Philippines (Nie *et al*., 2012). Similarly in Brazil, various studies revealed a decline in rice production after 2 consecutive seasons of growing upland rice, and after 5 years of monoculture, rice productivity was merely 1.5 t/ha, whereas a productivity of 4.3 t/ha was realized when rice was grown after 3 years of soybean cultivation (Kumar *et al.,* 2015).

Constraints

Some of the important limitations in aerobic rice cultivation are abundant weed infestation, poor plant growth, crop lodging, higher rate of panicle unproductiveness and root-knot nematode infestation. Significantly, profuse weed growth is the key limitation for aerobic rice which also requires high inputs like herbicides and energy for controlling the same. The unpuddled condition in aerobic rice ensued influx of nematodes and is touted as main constraints encountered in aerobic rice field (Kreye *et al*., 2009; Nie *et al*., 2012; Aleksza *et al*., 2017) and resulted in yield loss by 12–80%. Additionally, owing to higher percentage of penetration of water as well as variation in availability of nitrogen causes the aerobic soil to be more deficient in minor nutrients (Fe and Zn) and enhances nematode invasion (Das, 2014; Sarwar *et al*., 2017). Hence, administrations of balance nutrient and integrated weed management can be considered as the important thrust areas for profitable farming of upland rice. Weeds are the major limitation to extensive cultivation of upland rice (Yadav *et al.,* 2017). Weed problem in direct-seeded upland rice is notably higher than transplanted paddy (Singh *et al.,* 2016). In areas with a lesser seed rate, weeds have more possibility to germinate, develop, and producing profuse populations which ultimately lead to a serious threat of crop-weed competition. Thus increasing seed rate up to 125 kg/ha have been noticed to diminish weed population in dry, direct-seeded aerobic rice (Anwar *et al*., 2010; Mahajan *et al.,* 2010; Chauhan *et al*., 2011). Therefore, cultivation of genotypes with high competitive advantage against weeds was reported to be cost-effective as well as safe methodology for integrated weed-management (Singh *et al*., 2017). To attain efficient, long-term, and viable weed management in aerobic rice, it is essential to incorporate various weed management techniques, viz. cultural, physical and biological, and judicious use of herbicides as the last option instead of single weed-control option (Chauhan *et al*., 2011; Jabran and Chauhan, 2015). Many soil-borne pests and diseases have varieties of growing environment in aerobic soils where particularly root-knot nematodes (RKN) have been revealed to be most challenging when the method of cultivation becomes partly or completely aerobic. Usually amongst biotic factors, nematodes were assumed to be an important cause accountable for the difficulties arising during continuous cultivation aerobic paddy (Jadeyegowda *et al.,* 2019). Additional studies revealed that, root-knot nematodes were the main contributor for reduction in aerobic rice production (De Waele *et al*., 2013; Galeng-Lawilao *et al*., 2018). Jiban *et al.* (2019) investigated the fungal flora on and in roots of continuously cropped aerobic rice where they observed that only *Pyrenochaeta* spp. were notable. These fungal spices affect the development of aerobic rice via releasing some compounds which inhibit initial establishment of upland paddy seedlings.

CONCLUSION

Aerobic rice can be a feasible alternative for cultivating rice in moisture-shortage areas as well as through proper management, up to 80% yield achievable in flooded situation. The major benefit of aerobic rice than flooded rice is the minimization in irrigational water utilization. Upland rice farming enhances the water productivity and resulted in conserving water up to 37–45% over puddled rice system. Numerous techniques have been developed to defeat hindrance associated with continuous farming of upland rice. In suitable climatic environment and appropriate weed management, the productivity gap between aerobic and flooded ruce can be reduced. Additionally, during shortage of rainfall or dry areas, aerobic rice will be the most suitable alternative for cultivating rice, as traditional flooding method of growing of rice would not be feasible. Most importantly, cultivating aerobic rice would enable to reduce the release of greenhouse gases from rice farms with no effects on the yield.

Future research thrust

The possible cause of the productivity reduction under continuous aerobic rice cultivation is not yet identified. Studies may be initiated to understand the possible reasons which are accountable for the difficulties in continuous cultivation of aerobic rice as well as developing some mitigations mechanisms essential to achieve sustainability of aerobic rice cultivation. Future study on aerobic rice should also focus on the deficiencies of various minor essential elements and on special breeding programme for development of suitable cultivars of upland rice for the Indian subcontinent as well as semiarid zones of the globe. The aerobic rice breeding programme is very small and their genetic source is extremely narrow in comparison to lowland rice breeding. Investigators have to produce some definite aerobic rice genotypes with better yield capacity and wider tolerance range to both biotic and abiotic stresses.

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