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Present Research Priority on Aerobic Rice Culture for Sustainable Rice Production under the Backdrop of Shrinking Water Resource Base: A Review

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ABSTRACT

Rice plays a pivotal role in food security and global agricultural economy. Rice production sustainability to be assured and accelerated for feeding burgeoning population on the backdrop of scarce water resources. Flooded rice requires 900-2250 mm of water which leads to increasing water shortage. The rice production sustainability is threatened due to arsenic calamity and emission of greenhouse gases causing global warming. Aerobic rice culture technology is paradigm shift in rice production to increase water and crop productivity under the backdrop of shrinking water resource base requiring less water and the crop is grown non flooded or saturated with an added advantage of 50-80% lesser emission of methane. Significant differences in energy balance and evapo-transpiration, water productivity indicates that aerobic rice is one of the promising water saving technologies being developed to lower the water requirement of the rice crop to address the issue of water scarcity in tropical agriculture. Literature reveals that radiation use efficiency (RUE) in aerobic culture is comparable to or higher than that in flooded culture. Water inputs in aerobic rice are 50% lower (only 470 mm - 650 mm), 64-80% higher water productivities, 28-44% lower gross return, 55% lower labor use than flooded rice. But, micronutrient deficiencies especially Fe and Mn due to change in soil redox potential, infestation of root knot nematodes and interaction of biotic- abiotic stresses, increasing soil pH and high weed pressure led to yield failure or severe yield penalty in some cases. Grain yield reduction up to 25% or more has been reported by aerobic crop. This article reviews the possible interventions and modifications in morphological and physiological traits, appropriate breeding strategies for development of ideotype for aerobic situation on nutrient and weed management, water productivity and bio-energetics for sustaining rice production for immediate future to avert water scarcity and ensure food security.

Key words: Aerobic rice, Allometric slope, Eddy Covariance, Energy balance, Fe deficiency, Root knot nematode, Scarce water resources, Weed pressure.

Rice *(Oryza sativa* L.) is the staple food crop of the world and supports the livelihood of more than 100 million farm families providing energy requirement of billion of people and playing a pivotal role in agro-ecosystem and bio-diversity. Global requirement of rice is expected to be about 280 million tonnes produced in the next 30 years and feeding more than 9 billion people by 2050 will require doubling of production on sustainable basis (Midya *et al*., 2021, FAO, 2016). In India and China, which together hold about half the world's rice area, about 63-65% people are rice consumers and India is the second largest rice exporter after Thailand. More than three-fourths of rice output in India is realized on 79 million hectare of irrigated lowland and it is predicted that 17 out of 75 million hectares of Asia's flood irrigated rice crop will experience physical water scarcity and 22-million -hectare areas may experience economic water scarcity (Patel *et al*., 2010, Midya *et al*., 2017). The demand for rice in Asia will continue to increase as population in the region grows inline with economic development (Katsura *et al*., 2010). The rate of rice yield increases is declining, while water and land resources for rice production speciallyin Asia are becoming scarce. The sustainability of rice production is threatened due to indiscriminate over lifting of ground water in flooded rice culture leading to the arsenic contamination in some parts of the Indo-Gangetic plain zone of India and Bangladesh sometimes referred as the biggest arsenic calamity of the world. It is already been recognized that ground water used for irrigation of rice in arsenic affected parts of the countries poses an additional health hazards to people eating food from the crops irrigated (Williams *et al*., 2005) and that arsenic accumulation in irrigated soils poses a serious threat to sustainable agriculture in affected areas (Brammer, 2009). Moreover there is worldwide concern about global warming. Agriculture contributes approximately 20% of the annual increase in anthropogenic greenhouse gases by emission

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of carbon di-oxide, methane and nitrous oxide gases. Methane has highest global warming potential which is about 300 times the potential of carbon di-oxide and about 20 times that of nitrous oxide. The main sources of greenhouse gas in agriculture are flooded rice fields, nitrogenous fertilizers applied in submerged rice fields, faulty soil and water management. The people of rice growing nations throughout the world need to seriously ponder as to how long the rice production sustainability will continue as per the projected demand to feed the burgeoning population has to be fulfilled on the backdrop of declining land and water resources, and costly inputs which are making rice cultivation an expensive. There is growing awareness about the need to optimize water use in rice production. There should be paradigm shift in technology for rice production towards maximizing output per unit of water to ensure production of more crops from every drop of water as it is going to be serious constraints in irrigated ecology. Aerobic rice culture is an emerging agronomic production system that uses much less water than conventional flooded culture (Midya *et al*., 2021, Humphreys *et al*., 2010) wherein crop is established in non- puddle, non-flooded fields (Patel *et al*., 2010) to address the water crisis and reduction of methane emission in aerobic culture. The ecological intensification platform has been already designed as a futuristic advance agronomic research in which the efficiency of water useand other agronomic inputs is to maximize to develop highly productive rice based triple cropping systems with sustainable ecological footprints using water saving technologies. The purpose of the review is to document the research strategies of aerobic rice system for sustainable rice culture with an anticipation that this will be useful for other researchers seeking to increase crop and water productivity, profitability of aerobic rice. Aerobic rice as water saving alternative technology of rice production, varietal development,morphological and physiological traits, crop management, causes of yield decline and other related current research strategies in relation to aerobic rice aimed to increase the efficiency of aerobic rice will be prioritized, presented and discussed.

Aerobic rice as water saving alternative to avert future water scarcity and food security

Food security in Asian countries largely depends on irrigated rice consuming more than 50% of the water used for irrigation. Flooded rice requires 900-2250 mm of water (1500 mm on an average) depending on water management, soil and climatic factors; the sustainability of lowland rice fields is threatened by increasing water shortage (Bouman and Toung, 2009). The share of agriculture in total water use may reduce from present 83% to 72% in 2025. Water will be increasingly scarcer for agricultural purpose and the traditional flooded rice crop may not be feasible any more in many environments (Clerget *et al*., 2014). Increasing scarcity of fresh water for agriculture and the competing demand for water from the non-agricultural sector threaten the sustainability of the irrigated rice eco-systems (Albarto *et al*., 2012). The area of irrigated rice paddies experiencing physical water scarcity is rapidly expanding worldwide (Kato *et al*., 2010). Recognizing the water constraints to rice yield was to develop water efficient aerobic rice technology **(**Midya *et al*., 2021, Bayot and Templeton, 2009).

Aerobic rice requires 30-50% less water compared with flooded lowland rice (Midya *et al*., 2021, Bouman *et al*., 2005). The requirement of water inputs is much less as compared to traditional paddies and water productivity is much better than flooded culture. Aerobic rice is not ponded and irrigated similar to other upland cereal crops and grows in unsaturated conditions with adequate inputs and supplementary irrigation when rainfall is insufficient and suitable for water scares environments (Xiaoguang *et al*., 2005). Aerobic rice promises substantial water savings by minimizing seepage, percolation and greatly reducing evaporation (Chan *et al*., 2012). Casestudies showed that yields to vary 4.5 -6.5 t /ha which is about double than that of traditional upland varieties and about 20-30% lower than that of lowland paddies under irrigated conditions, whereas water use was 60% less than lowland rice, total water productivity 1.6-1.9 times higher and net return to water use is two-fold higher, lesser greenhouse gas emission and higher carbon credits (Lal *et al*., 2013).

The current scientific research challenge is to find agronomic system and improved varieties that can obtain stable yields comparable with those in flooded conditions when using limited water resources (Clerget *et al*., 2014) and integrate aerobic rice as a regular component of cropping system to make it an economically attractive crop production system for sustainable rice production under the backdrop of shrinking water resource base.

Potential genotypes for sustainable aerobic rice production and ideal physiological and morphological traits

Aerobic rice varieties are bred by combining the drought resistance of upland cultivars with the high yielding characters of lowland cultivars (Atlin *et al*., 2006). The technological development of aerobic rice varieties started in China in 1980s for breeding high yielding rice varieties 'Han Dao', Dry rice. In 2001 International Rice Research Institute (IRRI) commenced collaborative research with China Agricultural University, National Irrigation Administration in Tarlac and Philippine Rice Research Institute and started breeding program for tropical aerobic rice that ushered in the genotypic development of aerobic rice all throughout the world. The developed varieties have potential for sustainable rice production (Table 1).

Yield penalties under aerobic conditions were associated with reduced height and harvest index, whereas biomass at anthesis was similar even higher biomass in aerobic crops until anthesis caused by delay of 7-14 days in both maximum tillering and anthesis dates (Clerget *et al*., 2014). The relatively high harvest index resulted from high percentage of filled grains of aerobic genotypes (HD 502

and HD 297) compensated for their relatively short growth duration so that their yields higher than the lowland genotypes in China (Bouman *et al*., 2006)

Experimentally growing high yielding lowland rice genotypes under aerobic conditions have shown great potential to save water but with severe yield penalty (Peng *et al*., 2006). In South India aerobic rice genotype PMK 3 recorded maximum grain yield with less water (Parthasarathi *et al*., 2012). The adopted aerobic rice genotypes exhibiting drought tolerance have shown promising results but the yields still below the lowland rice in Malaysia (Chan *et al*., 2012). The development of high yielding aerobic rice is still in its infancy and germplasm needs to be improved.

Breeding Strategies for ideotype development

Research accomplishments in the last three decades have successfully led to the identification and prioritization of various physical, biological and technological constraints limiting productivity of upland rice in South and South East Asia. The area of upland rice is 18 m ha out of which 42% is in South East Asia where drought, weed infestation, blast, brown spot, insect pest are the predominantly retardant factors limiting productivity of rice. Only blast disease can cause economic losses up to US $ 60 million annually in South and South East Asia. The strong priority for blast resistance in the aerobic rice breeding programme, despite the effort made to produce and release blast resistant varieties; their average life is very short due to high variability in the eco-system.

Conventional breeding, breeding with marker assisted selection (MAS), development of hybrids for exploitation of heterosis, transgenic are the strategies for the breeding programme for aerobic rice development. Incorporation of multiple traits into high yielding varieties is governed by major and minor genes. Roots are the principal plant organ for nutrient and water uptake and hence understanding of interaction between root function and drought in rice will be important for breeding programme in aerobic rice. Bulk method of selection is advantageous for root characters whereas pedigree method of breeding is superior to bulk or modified bulk method for development of productive breeding lines. Genotype × input management interaction helps in breeding genotypes. According to Mandal *et al*. (2010) heritability for grain yield was similar for both moderate and low input condition and harvest index was highly correlated with grain yield. Information on heritability and gene action of a plant trait is a prerequisite for successful breeding programme (Gowda *et al*., 2011). Production of germplasm that can be exposed to mild early drought stress without sacrificing yield or reducing development rate (widely used in Australian breeding programme), conventional screening of high yielding lowland rice (widely used in Philippines), selection of varieties according to early season vigor targeting faster canopy closure (used in Arkansas) early tolerance to drought are the breeding strategies for development of aerobic rice genotypes. Breeding programme at China targets development of drought tolerance in aerobic rice genotypes by crossing lowland rice having high yield potential, poor drought tolerance with upland rice that has low yield potential with more drought tolerance with increased stomatal control and deeper roots. Achieving drought resistance in rice will be necessary for meeting the growing water shortage of the world, as it requires deeper understanding of the mechanisms that facilitate drought resistance (Serraj *et al*., 2011) and understanding of physiology of drought response can contribute to plant breeding efforts towards drought resistance in aerobic rice development.

Hybrid rice has a more vigorous root habit than inbred, this character translated into greater drought tolerance and greater biomass production under consistent drought condition however performance of hybrid under aerobic situation needs extensive research under different management practices and stress environment. Drought tolerance trait through transgenic rice is difficult to achieve, however for increasing water use efficiency through improvement in transpiration efficiency transgenic may play some role in breeding of aerobic rice. Recent studies have indicated that, apart from conventional and marker-assisted selection, potential exists for the transgenic approach to enhance drought resistance in plants by incorporating genes that are involved in stress tolerance (Hervé and Serraj, 2009). Transgenic cross between *Oryza sativa* and *Echinochloa caudata* under the leadership of Dr Ming Zhao at Chinese Academy of Agriculture developed Han Dao 65 variety having more than 30% photosynthetic efficiency in F_2 than both the parents which gave a ray of hope to the plant breeders for development of C_4 rice and Scientists at IRRI are doing research activities to this direction.

Molecular breeding can contribute to drought tolerance, pest disease resistance, nutrient use efficiency

Table 1: Potential aerobic rice genotypes for different countries.

Countries	Varieties/Genotypes	Yield potential
China	Han Dao 502, Han Dao 297, Han Dao 277	6 t/ha
Philippines	Apo (PSBRc 9), UPLRi5,PSBRC 80	5-6 t/ha
Malaysia	Apo AERON 1	5-6 t/ha
India	Pusa Hybrid 10,Pro Agro 6111, Pusa 834, IR 55423-01 (Apo1), Vandana, Virendra, Sahbhagidhan, CR Dhan 40, PMK 3	>4t/ha
Laos	B 6144F-MR-6-o-o	3.6 t/ha
Indonesia	Way Rarem	4-5 t/ha

and quality characters but none of the identified quantitative trait loci (QTL s) had large effect on grain yield. According to Miah *et al.* (2013) breeding with MAS is more efficient and reliable than breeding with phenotype selection. Marker assisted backcross breeding (MABC) may be used to introgressQTLs for root traits. Molecular markers like simple sequence markers, restriction fragment length polymorphism, single nucleotide polymorphism, polymerase chain reaction based allele specific markers have facilitated gene introgression process and gene pyramiding. Wen and Gao (2011); Sing *et al*. (2012); Gouda *et al*. (2013) reported that blast resistance genes pi1, pi5, piz-5, pi54, pita, Pi 9, Pi2, Pid1, pib have been introgressed in various elite rice genotypes utilizing MAS.

Morphological and physiological aspectsfor aerobic situation

Yield reduction in aerobic rice has been reported by different research workers. Conversely, Kato *et al*. (2009) reported no yield reduction or even higher yield in aerobic rice compared to flooded culture. Morphological and physiological modification play crucial role in growth and productivity of aerobic rice. Patel *et al.* (2010) from North – East Hill (NEH) ecosystems of India revealed that the yield difference between aerobic (1.67 t/ha) and flooded rice (2.31 t/ha) ranged from 18.4 to 37.8% ($P<0.05$) depending on varieties, highest difference being observed with rice hybrid. Cultivation of rice under aerobic condition resulted in 27.5% yield reduction over flooded rice and among the yield components assessed, sink size (spikelets per panicle) contributed more to the yield and is considered to be most important factor responsible for yield gap between aerobic and flooded rice. The variety with moderate values of photosynthesis rate, transpiration rate and water use efficiency (WUE) along with higher grain yield seems to be better choice for both stress (aerobic) as well as normal (flooded) condition. Aerobic rice varieties with minimum yield gap compared to flooded rice is the key for success of aerobic rice cultivation. A recent study conducted in Japan indicated thatgrain yields were 25% lower in the aerobic crop as a result of a complex series of modifications and adjustments in plant architecture and yield components resulted from four main changes-higher plant density, slower rate of leaf appearance, lower nitrogen content and reduced size of all organs induced by the aerobic crop environment were responsible for three chains of modifications that reflects in lower biomass accumulation and finally lower grain yield and lower nitrogen content with biphasic biomass accumulation (Clerget *et al*., 2014). In aerobic fields, the allometric slope (*i.e.*, the ratio of shoot size to shoot number) was lower than in flooded culture, and was further reduced by increased soil water deficit. The allometric slope is significantly correlated with the area of 9th leaf. The area of 9th leaf is greater in aerobic culture. Among the nine cultivars from a study by Okami *et al*. (2012) in Japan reveals that slight change in the allometric slopewas associated with larger variation in leaf area in aerobic culture than in flooded culture. Consequently, among cultivars with larger leaves (shoots), mediated by a higher allometric slope, were advantaged compared to those with smaller leaves with respect to early vigor under limited soil moisture. A significant relationship between leaf size and early vigor was also observed for the cultivars grown in aerobic culture confirming the existing perception that tropical japonica cultivars are useful genetic sources for yield stability because of their ability to maintain large shoot size despite fluctuations in hydrological conditions.

Plants use different mechanisms to cope with drought stress, namely, drought escape, drought tolerance, drought recovery and drought avoidance. Among these four mechanisms, the mode of drought resistance with which roots are most likely associated is drought avoidance. Genotypes that have deep, coarse roots with a high ability of branching and penetration, higher root to shoot ratio, elasticity in leaf rolling, early stomatal closure, and high cuticular resistance are reported as component traits of drought avoidance (Gowda *et al*., 2011). Many studies have restricted their analyses to a set of root parameters that include root development with respect to tiller development, maximum root depth, total root length, root surface area, root volume, root diameter, root length density, root distribution pattern in the soil column, root to shoot ratio, root branching, root hydraulic conductance, root anatomy, root elongation rate, total plant length and hardpan penetrability and these have various functional significance for tolerance of stress.

Morphological traits is also associated with soil water potential. From a study conducted by Kato *et al.* (2010) from Japan it was reported that in aerobic culture, where the soil water potential at 20-cm depth averaged between -15 and -30 kPa, total root biomass was significantly lower than in flooded culture for the whole growing period, owing to a reduction in root biomass in the surface layer while dry-matter partitioning to roots decreased, but the ratio of deep root biomass to total root biomass tended to be higher in aerobic culture than in flooded culture. The stomatal behavior reflected the root growth in the subsurface layer which suggests the role of vigorous root growth in soil water uptake and hence, in maintainingtranspiration in aerobic rice culture. According to the review of Gowda *et al*. (2011), as root traits are generally controlled by quantitative trait loci (QTL) many QTLs related to root traits have been identified in rice using different mapping population.

All possible strategies to be deployedfor comparison of estimates of total root length andfine root length of rice in aerobic culture and flooded condition to have a comprehensive understanding of root traits which may aidin identification of suitable genotypes having root characteristics adaptable to aerobic situation. Comair root length scanner detect fewer fine roots ranging between that of roots wider than 0.1 mm but the roots wider than 0.2 mm estimated by image analysis software (Kato *et al*., 2010).

The root length measurement by image analysis software is still in infancy, this new tool will facilitate the phenotyping of root system architecture and shed light on the roles of fine roots in water-saving rice cultivation. Information pertaining to physiological basis of yield gap between aerobic and flooded rice is vital for identifying the physiological and morphological traits to support the selection and breeding of high yielding aerobic rice varieties. There should be compromise between physiological traits and yield of a particular variety while identifying a variety under stress condition. Patel *et al.* (2010) reported that photosynthesis rate, leaf temperature were significantly higher under aerobic condition, whereas stomatal conductance was higher in flooded condition, transpiration rate and leaf temperature depression was statistically similar. The physiological traits of high yielding characters like chlorophyll content, efficiency of photo system II, soluble protein content, photosynthetic rate, stomatal conductance should be amalgamated with drought tolerant character like relative water content, compatible osmolytes like proline, scavenging enzymes like CAT, POX, SOD. Gene expression analysis helps in identifying the functionally important genes and pathways involved in root architecture in rice under water-deficient conditions. Under this backdrop, genomics and proteomics can play vital role for development of ideal plant type for aerobic situation.

Nutrient management

Aerobic soil is diverse in nature.Soil pH under conventional puddle transplanted rice approaches to neutral equilibrium which offers great opportunities for rice cultivation under varied agro-ecosystem, more over flooded rice ecosystem has a great ameliorative effect on chemical fertility resulting in better availability of plant nutrients, accumulation of organic matter and enhancement of biological N fixation that supplies the crop with additional N. Aerobic rice soil will no longer approach to neutral equilibrium due to positive redox potential and nutrient availability is also a concern in aerobic rice cultivation, as the soil redox potential becomes positive, the availability of Fe and Mn decreases. As evidenced from research work of Rong Li *et al.* (2012) that there is inadequate nutrition of rice plant due to change in soil moisture regime and P deficiency in aerobic soil needs special attention for nutrient management and iron deficiency is the common nutritional problem in aerobic rice production. Production practices for rice cultivation are shifting from flooded-rice to aerobic rice to make more efficient use of irrigation water. This shift has brought about increases in Fe deficiency in rice, a new challenge depressing iron availability in rice and reducing Fe supplies to humans. On the contrary Zn and sulphur should be more available in aerobic soil and there should be no additional issues with potassium. Site specific nutrient management is the most effective tool for nutrient management and utilization of leaf color chart and possible options for increasing N and P efficiency, optimal fertilizer dose and agronomic interaction with nutrient supply play a vital role for nutrient management in aerobic rice. Study from Xiang *et al*. (2009) reveals that soil acidification can improve the growth of aerobic rice and nitrogen uptake. Haden *et al*. (2011) and Qi *et al*. (2012b) reported that poor growth of aerobic rice associated with urea application induced ammonia toxicity when applied at seeding. In high soil pH condition, it is much important that improving nitrogen use efficiency and reducing nitrogen loss by ammonia volatilization. Loss of Ammonia can be avoided by deep placement of urea and slow release nitrogen; mixture of nitrate and ammonium nitrogen gives superior nitrogen nutrition in aerobic rice. Slow release formulations of nitrogen may be well suited to increasing nitrogen use efficiency (NUE) in aerobic culture and controlled release of nitrogen can increase NUE from 35-40 per cent to 80% by reducing ammonia volatilization after top dressing and de nitrification from an aerobic system. Xiang *et al.* (2013) from an experiment reported that plant growth parameters of aerobic rice under ammonium sulfate were significantly higher than urea, N placement at a depth of 5.0 cm in the soil significantly reduced nitrogen loss by ammonia volatilization. There is a possibility of improving aerobic rice yield in the continuous aerobic rice system by using right N source or changing conventional method of nitrogen application to deep placement. Lampayan *et al.* (2010) while evaluating the effects of amount and timing of fertilizer nitrogen (N) application and of row spacing on the yield of aerobic rice under rainfed conditions in Philippines explained that yields increased with N rate, up to rates of 60 kg ha^{-1} depending on site and season, but at rates beyond 90 kg ha^{-1} the risk of lodging increased, especially in the wet season whereas yields were similar for different splits of N over time and the regional practice for lowland rice of three to four splits can also be used for aerobic rice. It was revealed from the study by Kreye *et al*. (2009a) with three N fertilizer treatments (ammonium sulfate, urea, no application) and two soil water conditions (well drained and water-logged) that irrigation water from the field site increased soil pH, impaired plant growth and induced chlorosis. The application of ammonium sulfate reduced soil pH to values below 6 and increased plant micronutrient (Fe, Mn and Zn) contents and plant growth. Rong-Li *et al*. (2012) have explained the possible causes of Fe deficiency problem in aerobic rice which indicates that the amount of phytosiderophores (PS) released from aerobic rice did not increase under Fe deficient conditions. Current crop management strategies addressing Fe deficiency include Fe foliar application as advocated by Pal *et al*. (2008) and soil application and plant breeding for enriched Fe crop species and varietiesand selection of cropping systems. The nutritional quality of staple crops can be improved by integrated soil and crop management approaches, these practices would benefit human nutrition. Zuo and Zhang (2011), Rajendra Prasad *et al*. (2014) have recommended the combined use of multiple strategies for Fe enrichment

of food crops with bio-fortification that will offer more effective and sustainable pathways to alleviate micronutrient malnutrition. Hence, to overcome iron deficiency in aerobic rice as well as increasing iron density in rice grain and human food, we need integrated crop management strategies. Yadav *et al*. (2013) reported that growing of aerobic rice with *Sesbania* mulch and Fe fertilization for production of higher grain and straw yield of aerobic rice with sufficient Fe nutrition.

For better phosphorus nutrition in aerobic rice, application of phosphate solubilizing microorganisms play vital role and marker assisted breeding for introgression of PSTOL 1 gene having potential for better P use efficiency which is major limiting factor in aerobic rice soil. However, continuous and increased use of chemical fertilizers alone lead to several harmful effects on the soil, ground and surface water and even causing atmospheric pollution and reducing soil productivity by adversely affecting soil health in terms of physical, chemical and biological properties. Integrated nutrient management strategies have been proposed to include simultaneous use of inorganics and organic materials and bio-fertilizer as the most effective method to maintain a healthy and sustainable soil plant system while increasing the productivity (Midya *et al*., 2021). It is evident from the research work of Paramesh *et al*., (2014) that integration of 50% recommended dose of nitrogen through vermicompost with 50% recommended dose of nitrogen through chemical fertilizer register significantly higher plant height, leaf area, number of tillers per hill, total dry matter content and finally grain and straw yield in aerobic rice. In a recent research work by Midya *et al.* (2021) it is being recommended for adoption of INM in aerobic rice culture for improving nutrient uptake, use efficiency, yield enhancement and soil quality.

Water management and energetics

The driving force of aerobic rice culture is higher water productivity and optimum utilization of natural resources. It is reviewed by Parthasarathti *et al*. (2012) that aerobic rice saved 73% of irrigation water for land preparation and 56% during the crop growth period. Aerobic rice with micro irrigation practices leads sustainable rice production methodology for immediate future to address water scarcity with more benefits and environmental safety in the scenario of global warming by reduced methane emission is an added advantage. Study conducted by Bouman *et al*. (2005) reflected that reduction in water use during land preparation and limiting seepage, percolation, evaporation, aerobic rice had about 51% lower total water use and 32-88% higher water productivity, expressed as gram of grain per kilogram of water, than flooded rice. Numerous studies pertaining to grain yield of rice under different crop establishment methods and irrigation treatments have been conducted and extensively studied by several workers *viz*., Midya *et al*. (2021), Bouman *et al*. (2005, 2009); Bhusan *et al*. (2007); Chan *et al*. (2012) *etc.* In China, compared with lowland rice, water inputs in aerobic rice were more than 50% lower (only 470 mm-650 mm), water productivities 64%-88% higher, gross returns and labor use 28%-44% and 55% lower respectively (Bouman *et al*., 2005). Since aerobic rice is targeted at water-short areas, socio-economic comparisons must include water-short lowland rice and other upland crops. Experimental findings reveal that with supplementary irrigation, grain yield obtained ranged from 2.2 to 3.6 t/ha and the seasonal field water requirement was between 442 and 763 mm (Chan *et al*., 2012). Light and frequent irrigation was better when compared to heavy and occasional irrigation to avoid unnecessary water stress that could cause yield reduction.

Yield reduction of 50% was recorded if water stress occurred during heading and early grain formation periods.Despite lower crop yield studies showed that aerobic rice cultivation used much less water for production. This in turn improved water productivity from 0.4 to 0.6 kg/m^3 compared to irrigated wetland rice. It is reflected from an experiment conducted by Midya *et al*. (2021) that Irrigation Water Productivity and Total Water Productivity in aerobic rice was registered 2.28 kg grain/ m^3 and 0.72 kg grain/m^3 of water respectively under Indo-Gangetic Plain zone of India, and in terms of energy efficiency aerobic rice culture registered significantly higher energy efficiency(13.03) and energy productivity (0.413 kg/MJ) as compared to conventional puddle transplanted rice ecology. The reduction in the water used was mainly attributed to the reduced seepage and percolation losses, decrease in evaporation since there was no standing water in the field, and also water required during pre-saturation period for land puddling was completely discarded. Pressurized irrigation systems (sprinkler, surface and subsurface drip) have the potential to increase irrigation water use efficiency by providing water to match crop requirements, reducing runoff and deep drainage losses, and generally keeping the soil drier, reducing soil evaporation and increasing the capacity to capture rainfall however susceptibility to foliar diseases has been documented by researchers in sprinkler irrigation (Chan *et al*., 2012). Relative water content also decline due to severity in aerated condition in sprinkler irrigation coupled with high transpiration rate (Sritharan *et al*., 2010).

Crop production is an energy conversion process and efficiency of crops in terms of energy utilization depends on the capacity of the plant to accumulate maximum dry matter, aboveground nitrogen by utilizing less energy and radiation. Naturally energetics in crop production is quantified by various methods and studies. Seasonal and annual distribution of heat fluxes and evapo-transpiration, environmental and bio-physical variables affecting the fluxes play significant role in crop energetic. So far as rice cultivation is concerned, evapo-transpiration is largest consumer of available energy consuming 60-80% of net radiation in a growing season playing vital role for field water cycle influencing crop growth, development and yield. Several studies on the energy and CO_2 exchanges have

been conducted in flooded rice by several techniques *viz*. coupled land surface and crop growth models to estimate the effects of changes in the growing season on the energy balance and water use of rice paddies in Japan (Maruyama and Kuwagata, 2010). Eddy co variance technique (Zhao *et al*., 2008) to study the effects of conversion of marshland to rice and soybean cultivation on water and energy exchanges in north eastern China, surface energy components and land characteristics of a rice paddy in Taiwan (Tsai *et al.,* 2007), flux variance and surface renewal method to estimate sensible and latent heat fluxes and comparison the results to the direct measurements using EC(Eddy Covariance) technique (Zhao *et al*., 2010; Castellvi and Snyder, 2009; Hsieh *et al*., 2008), the nature of vertical transport of sensible heat and water vapour density, however studies on energy and carbon dioxide (CO_2) exchanges in aerobic rice ecosystems are comparatively lacking. Facchi *et al*. (2013) explored the possibility of using only one eddy covariance system for monitoring the heat and water vapor fluxes in two rice environments, flooded and aerobic in Italy through monitoring and modelling approaches of evapotranspiration and found a very good agreement between measured and simulated data for flooded culture, while a slight over estimation of the simulated values compared to measured ones for aerobic situation as evidenced from the slope of regression. Alberto *et al*. (2011) in the Philippines investigated the seasonal and annual variability of sensible heat flux (H), latent heat flux (LE), evapotranspiration (ET), crop coefficient (Kc) and crop water productivity (CWP) under two different rice environments, flooded and aerobic soil conditions, using the eddy covariance (EC) technique and concluded that flooded rice fields had 19% more LE than aerobic fields whereas aerobic rice fields had 45% more H than flooded fields. The average annual ET was 1301 mm for aerobic rice and 1440 mm for flooded rice. This corresponds to about 11% lower total evapotranspiration in aerobic fields than in flooded fields. However, the crop water productivity (WPET) of aerobic rice (0.42 grain kg^{-1} water) was significantly lower than that of flooded rice (1.26 g grain kg^{-1} water) because the grain yields of aerobic rice were very low since they were subjected to water deficit under temporary declines in soil moisture in aerobic culture and the ability to maintain high nitrogen percentage in flooded culture. According to Bouman and Tuong (2009) under aerobic conditions, mean RUE (Radiation use efficiency) over water treatments dropped to 1.70-1.72 g DM MJ^{-1}. with increasing dryness of the soil, the amount of intercepted light decreased at about the same rate for all aerobic crops, but RUE decreased faster in the lowland than in aerobic culture. Katsura *et al.* (2010) demonstrated through an experiment with four high yielding rice cultivars at two sites in Japan that biomass production of 20 t/ha was attainable in aerobic culture due to accumulation of larger quantity of N at ripening stage and RUE in aerobic culture was comparable to, or higher than, that in flooded culture (1.27 -1.50 g MJ^{-1} vs. 1.20-1.37 g MJ^{-1}) whereas total water input was 800-1300 mm and 1500-3500 mm in aerobic culture and flooded culture respectively.

Weed management

Aerobic systems are subject to much higher weed pressure due to simultaneous emergence of crops and weeds in absence of standing water at early stages of crops to suppress weeds (Chauhan and Johnson, 2010b) than conventional puddle transplanting systems (Rao *et al*., 2007; Singh *et al*., 2008) in which weeds are suppressed by standing water and by transplanted rice seedlings. Aerobic soil dry-tillage and alternate wetting and drying conditions, on the other hand, are conducive to the germination and growth of weeds resulting higher weed pressure coupled with greater grain yield losses (Mahajan *et al*., 2010) to the tune of 50-91% (Rao *et al*., 2007). Stress ecological situation which is detrimental for crop may be congenial for luxuriant growth and proliferation of weeds (Midya *et al*., 2005). Aerobic rice system has huge potential as a water-wise technology but its adoption has been impeded by serious weed problem (Rahman *et al*., 2012). While investigating the scenario of weed infestation and magnitude of yield loss in aerobic rice, Singh *et al*. (2008) reported that out of total weed flora infesting aerobic rice field grassy weeds constitute about 78-96% and yield loss due to weed infestation may be up to 38-92%. Thus, weeds are the most severe constraints to aerobic rice production and timely weed management is crucial to increasing the productivity. Application of chemicals may lead to phytotoxicity and adverse impact on agro-ecosystem and soil beneficial microorganisms. Ecological management of weeds in direct seeded rice stresses on shifting the crop weed balance in favor of rice by adopting the integrated approaches of all available tactics like cultural, physical and biological and finally judicious utilization of herbicides as last resort (Rao and Ladha, 2012; Midya *et al*., 2005; Banik *et al*., 2006). There has been increased interest recently in the application of cultural approaches, weed ecology and eco-physiological approach in integrated weed management systems (Chauhan *et al*., 2010). One approach is to reduce row spacing to improve crop competitiveness with weeds (Chauhan and Johnson, 2010a). As per study by Chauhan *et al.* (2011), the aerobic rice yields better in 15 cm rows and 10-20-10 cm arrangements than in 30 cm rows and there is very little benefit of weed control beyond 8 weeks after sowing. It is also important to study the weed physiology, weed ecology, weed community dynamics, weed emergence profile and weed seed bank to have better weed management. From a comprehensive study by Chauhan and Johnson (2010) it is reported that plant height of *Echinochlo colona* and *Echinochloa crus-galli*, two dominant weed flora of aerobic rice, was not influenced by the crop row, but it was influenced by the weed emergence time, weeds of either species emerging until 30 DARE (days after radical emergence) had greater biomass and more seeds under wide rows than under narrow rows, but row spacing had no significant effect on biomass and seeds of plants emerging

later suggesting that narrowing row spacing and controlling early weeds led to decreased weed growth and seed production and increased grain yield in aerobic rice. Simultaneous cultivation of smother/weed suppressive crops in rice field can effectively be utilized for weed management in aerobic culture. Deferred seeding of suitable legume crops in rice/wheat field is recommended as an eco-physiological approach for weed management, soil fertility restoration and in addition yield advantages (Midya *et al*., 2005; Banik *et al*., 2006). Brown manuring is an emerging technology of weed management in aerobic rice culture where the seeds of *Sesbania aculeata* are simultaneously sown with rice and knocking down it with the application of herbicides (Midya *et al*., 2021). Juraimi *et al*. (2012) from an experiment reported that seed priming enhanced the germination index and seedling vigor index to a great extent in aerobic rice due to reduction in weed dry matter ranging from 22 to 27 % compared to control. A positive influence of priming was also reflected in rice yield. Weed inflicted relative yield loss was curtailed by 10% as a consequence of seed priming. Breeding of aerobic rice cultivars combining both high yield and strong weed competitiveness (WC), with a reduced requirement for weeding is critical to the development of aerobic rice systems. Moreover, the adoption of weed-competitive cultivars will decrease environment pollution and development of herbicide-resistant biotypes by reduced herbicide application. Weed competitive cultivars are a low-cost and safe tool for integrated weed management (Zhao *et al*., 2006). Weed competitiveness of crops has two components: weed tolerance (WT), the ability to maintain high yields despite weed competition and weed suppressive ability (WSA), the ability to reduce weed growth through competition. Differences in WSA among cultivars can be directly determined by assessing weed biomass in plots under weed competition, but differences in WT can only be compared in terms of crop grain yield under weed competition among cultivars with the same yield potential and WSA (Gibson and Fischer, 2004). Zhao *et al*. (2006) reported that, traits associated with rapid seedling biomass accumulation were also strongly associated with weed suppression and yield under weed competition. In spite of all the available technologies considering the economics of cultivation use of suitable selective eco-friendly molecules of herbicides are becoming inevitable for proper weed management in aerobic rice culture. Combinations of herbicides ensuring broader spectrum of weed control and the herbicide selection should be based on the target weed species in addition to their broader category of grass, sedge and broadleaf for planning an effective weed control program for aerobic rice (Rahaman *et al*., 2012). Application of some pre-emergence herbicides including pedimethalin, butachlor, thiobencarb, oxadiazon, oxyfluorfen and nitrofen were found to provide a fair degree of weed control in wet direct seeded rice. But, application duration of all those pre-emergence herbicides is very narrow, usually 0 to 5 days of seeding, and they require adequate moisture during their application. Therefore, under aerobic soil conditions post-emergence herbicides like ethoxysulfuron, cyhalofop-butyl, pretilachlor, chlorimuron, metsulfuron, bispyribac sodium, penoxsulam effectively controlled weeds in aerobic rice (Mahajan *et al*., 2010; Juraimi *et al*., 2010; Rahman *et al*., 2012). The repeated use of same herbicide causes development of herbicide resistance in weeds and therefore, alternate application of herbicides with different modes of action would necessarily be needed to combat this troublesome situation.However for chemical weed control it is of utmost importance to screen suitable molecules at proper dose to be applied at right physiological growth stage of rice to avert phytotoxicity. Even AOPP and cyclohexanidiones group of molecules are typically grass killers, application of such herbicides at suitable dose in rice requires special care. It is a matter of great concern that *Echinochloa* sp has developed resistance to Propanil and cross resistance to Bispyribac sodium and cyhalofop butyl.Application of a single herbicide can't provide good weed control. Proprietary mixture or tank mixture of herbicides with different modes of actions appeared to be more effective than their single application. Among the herbicides pretilachlor/chlorimuron+metsulfuron followed by hand weeding was superior (Rahaman *et al*., 2012) in attaining higher net returns that are similar to those of weed-free situations under all methods of rice establishment.

Constraints of aerobic rice cultivation and intervention to alleviate the constraints

Although aerobic rice culture is a potential water saving methodology for rice production to avert water scarcity and sustain food security in tropical agriculture it has some impediments for adoption of the technology universally. Yield decline (Peng *et al*., 2006) rapid yield losses and yield failure due to soil sickness (Kreye *et al*., 2009a) have been reported in tropical environments. ''Soil sickness'' has been proposed to denote soil-borne abiotic and/or biotic stresses and interaction of biotic and abiotic factors (Sasaki *et al*., 2010) that result in poor crop growth and yield loss. Elements of soil sickness may be soil-borne pests and diseases (such as fungi or nematodes), the unavailability of nutrients, adverse soil structure, or allelopathy. Inadequate water supply in aerobic rice has detrimental effect on soluble protein and other physiological parameters of the crop leading to low productivity. Infestation of root knot nematode (RKN) and soil borne pest and diseases, excessive weed pressure, N deficiency, some micronutrient deficiencies particularly Fe and Mn (Kreye *et al*., 2009a) due to changes in redox potential of soil and high soil pH, changes in soil nutrient level and growth inhibition by toxic substances, continuous cropping obstacles (Nie *et al*., 2012; Peng *et al*., 2006) of aerobic rice are the major retardant factors for rice production sustainability under this system. Kreye *et al*. (2009a) reported about nematode infestation, incidence of

fungi was also pointed out along with growth inhibiting toxic substances. Several soil related problems are also addressed by several workers. Xiang *et al*. (2009) indicated the adverse impact on crop due to increased soil pH, some findings in an aerobic rice field experiment in the Philippines suggested a strong involvement of soil pH in yield failure of aerobic rice (Kreye *et al*., 2009b). However, resistant aerobic rice genotypes can overcome the problems of nematode (*Meloidogyne graminicola)* infestation in aerobic culture as reported by Das *et al.* (2012). It was reported that the aerobic condition when alternated with the anaerobic condition, or a fallow period, the production under aerobic treatment provides good yields and even two season fallow and three seasons of rotation with flooded rice also alleviate the problem of yield decline in aerobic rice and there are also evidences of potential benefit of legume-aerobic rice rotation due to better nitrogen nutrition (Nie *et al*., 2009; Midya *et al*., 2005).

CONCLUSION

With advancement in civilization, rapid urbanization water is going to be most scarce input in irrigated ecology to sustain rice production globally. Water saving rice technologies like aerobic rice have been developed to sustain rice production on the backdrop of shrinking resource base to address the issue of water scarcity in tropical agriculture. Research strategies in aerobic rice so far have been prioritized on the water economy, energetics and ecological intensification. Obviously fantastic water saving, energy balance is possible under this emerging agronomic production system, however yield penalties have been reported in various ecology throughout the world. So it is high time for concerted research in aerobic rice for improvement in stable genotypes deploying the available breeding technologies involving even genomics and proteomics, trait based approach with precise understanding of the target environment including temporal and spatial heterogeneity for the use of roots and dehydration avoidance traits for improved drought resistance, transgenic (C4 metabolism with transgenic crosses), soil management and bio-fortification to ameliorate nutritional deficiencies, intervention of micro-irrigation practices, integrated crop management with special emphasis on weed management with due consideration on eco-physiological approach, herbicide resistance, tolerance and pest management. Rigorous and systematic research strategies to be deployed to overcome the constraints limiting production under water efficient aerobic culture on the backdrop of shrinking resource base The technology may be a viable option for rice production sustainability for immediate future to address water scarcity with more benefits and environmental safety in the scenario of global warming without large investments in agro-ecology and associated heavy use of fresh water for conventional transplanted rice.

Conflict of interest

All authors declare that they have no conflict of interest.

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