GENETIC IMPROVEMENT OF RICE FOR AEROBIC CONDITION-A REVIEW

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ABSTRACT

Aerobic rice system is a new production system in which rice is grown under nonpuddled, non-flooded, and non-saturated soil conditions. New cultivars must be developed if growing rice like an irrigated upland crop is to be successful. Lowland cultivars have been selected to give high yields under continuously flooded lowland conditions. They generally suffer a yield loss due to water stress, weeds and non-availability of nutrients under aerobic condition. Upland varieties have been developed to give stable though low yields in adverse environments where rainfall is low and irrigation is absent. Therefore, high yielding aerobic rice varieties suitable for cultivation under aerobic conditions are warranted. Research programmes on genetic improvement of rice for aerobic condition had resulted in release of the first generation aerobic rice varieties with high yield potential and they can be cultivated in water shortage areas of lowland rice.

Key words: Aerobic rice, Genetic improvement, Water crisis

Irrigated rice is a profligate user of water. Water consumption per kg of rough rice ranges from 1000 to 5000 litres depending on climate, soil conditions, and crop management, and is about two to three times that of other cereals such as wheat or maize. In Asia, 90% of the total diverted fresh water is used for irrigated agriculture, and more than 50% of this is used to irrigate rice. There is a growing scarcity of water worldwide, which has already started to influence conventional irrigated rice production. By 2025, a ‘physical water scarcity’ is projected for more than 2 million ha of irrigated dry-season rice and 13 million ha of irrigated wet-season rice in Asia, and an ‘economic water scarcity’ is expected to hamper most of Asia’s 22 million ha of irrigated dry-season rice (Tuong and Bouman, 2002).

India accounts for 16 per cent of the world’s human population with only 2.4 per cent of the land area and 4 per cent of water resources. Even if the full irrigation potential is exploited, about 50 per cent of the country’s cultivated area will remain unirrigated with current level of irrigation efficiency (Planning Commission Report, 2007). Therefore, researchers are looking for ways and means to decrease water use in rice production and increase the water use efficiency.

A fundamental approach to reduce water inputs in rice is to grow the crop aerobically like an irrigated upland crop such as wheat and maize. Early experiments on aerobic rice revealed that water input in aerobic rice was 50% per cent lower (only 470-650 mm) and water productivity was higher by 64-88 per cent than the irrigated lowland rice (Bouman, 2001). Though, aerobic system of rice cultivation can save water up to 50%, intermittent water limitation and weed infestation in this cultivation approach results in yield reduction ranging between 15 and 40%. Besides periodic water stress and weeds, because of the positive soil redox potential values, several essential nutrients, especially iron and zinc become limiting for growth and productivity of rice. Developing suitable rice cultivars for aerobic conditions is essential to exploit the water saving potential of aerobic conditions.

Aerobic rice: Aerobic rice is a new way of cultivating rice that requires less water than lowland rice. It entails the growing of rice in aerobic soil, with the use of external inputs such as supplementary irrigation and fertilizers and aiming at high yields (Wang et al., 2002). Aerobic way of growing rice saves water by eliminating continuous seepage and percolation, reducing evaporation and eliminating wet land preparation (Castaneda et al. 2002).

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(i) Water saving in aerobic rice: A new development in water saving technology is the concept of “aerobic rice”. In aerobic rice systems, fields remain unsaturated throughout the season (Bouman et al., 2004). The target environments for aerobic rice are irrigated lowlands where water is insufficient to keep lowland paddy fields flooded and favourable uplands with access to supplementary irrigation. Irrigation can be by surface irrigation (e.g., flush irrigation, furrow irrigation) or by sprinklers and aims at keeping the soil “wet” but not flooded or saturated (Belder et al., 2005).

Bouman (2001) reported that in aerobic rice, irrigation would be applied to bring the soil water content in the root zone up to field capacity after it has reached a certain lower threshold (e.g., half way between field capacity and wilting point) or soil moisture tension at 15 cm depth reached -30 kPa (Castaneda et al., 2002).

Studies on non-flooded irrigated rice using sprinkler irrigation in the United States showed that irrigation water requirements were 20-50 per cent less than in flooded rice, depending on soil type, rainfall and water management (McCauley, 1990). Bouman et al. (2004) observed that water inputs in aerobic rice were more than 50 per cent lower (only 470-650 mm) and water productivities were 64-88 per cent higher than the lowland rice.

Kato et al. (2009) compared the potential productivity of aerobic rice and flooded rice using high-yielding varieties at two locations in Japan in two successive years and reported that in aerobic fields, the total amount of water supplied (irrigation plus rainfall) was 800-1300 mm. The soil water potential at 20 cm depth averaged between -15 and -30 kPa each growing season, but frequently reached -60 kPa. The average yield under aerobic conditions was similar to or even higher than that achieved with flooded conditions. The average water productivity under aerobic conditions was 0.8-1.0 kg grain m⁻³.

(ii) Methane emission and aerobic rice: In lowland system of rice cultivation, methane which is a major end product of anaerobic fermentation is released from the submerged soil to the atmosphere through roots and stems of rice plants. Its concentration in the atmosphere has more than doubled during the last 200 years. The global annual emission of methane is estimated to be 500 Tg (1 Tg = 1 million tonnes) with an apparent net flux of 40 Tg/yr. The current burden of methane in the atmosphere is approximately 4700 Tg. Continued increase in atmospheric methane concentrations at the current rate of approximately 1 per cent per year is likely to contribute more to future climatic change than any other gas except carbon dioxide (Shashidar, 2007). But in aerobic system of rice cultivation, as there will not be any anaerobic fermentation, methane production from rice fields will be totally curbed. In spite of several advantages in aerobic rice, due to shift from flooding of rice fields to aerobic system of rice cultivation, several factors are expected to change resulting in yield reduction. Development of suitable rice cultivars is highly essential to make aerobic rice a successful one.

Consequences of shift from lowland system to aerobic system of rice cultivation

(i) Micronutrient bioavailability: Many factors that determine bioavailability of essential elements are expected to change after a shift to aerobic system of rice cultivation. Soil pH is an important characteristic and controls the availability of most essential plant nutrients and thereby the growth and yield of rice. Flooding overcomes both acid and alkaline (sodic) conditions in soil. For example, Ponnamperuma (1972) reported that pH of an acid soil changed from 3.5 to near 6.0 and that of an alkaline soil changed from 8.1 to near 7.3 on submergence for a period of 2 weeks due to the dilution of H⁺ or Na⁺ ions and reverted back to its original pH when flooding was withdrawn. In aerobic rice, as the concept of flooding the paddy fields is abandoned, bulk soil pH may either increase or decrease depending on the original soil pH. In an aerobic rice study at Tarlan, Philippines, the pH of soil increased from 7.0 at seeding to near 8.0 at flowering in 2007 and was reported to be responsible for micronutrient deficiency (Kreye et al., 2009)

Zinc deficiency is one of the most common micronutrient disorders in rice, for both lowland varieties grown under flooded conditions and upland or aerobic varieties grown under aerobic conditions (Fageria, 2000). Zinc deficiency symptoms were observed in aerobic rice in North China, 2 or 3 years after fields were shifted from flooded to aerobic conditions (Wang et al., 2002).
Behavior of Zn in aerobic soils differs significantly from flooded soils because of drastic differences in physical, chemical and electro-chemical properties of soils (Ponnampuruma, 1972). Soil properties including pH, redox potential, organic matter and pedogenic oxides exert the most significant influence on the adsorption-desorption reactions of Zn in soils and thus regulate the amount of Zn dissolved in soil solution. These properties are expected to change after a shift from lowland to aerobic cultivation. Bulk soil pH will change from pH 7 towards the original soil pH. Redox potential will increase causing Fe oxidation, with concomitant acidification, precipitation of Fe(OH)₃ and adsorption of Zn on these oxides. Increased nitrification may cause plants to take up NO₃⁻ instead of NH₄⁺ which also causes the rhizosphere pH to increase. Organic matter on to which Zn can be adsorbed will be oxidized. Rhizosphere controls the bioavailability of Zn through changes in pH. Changes in pH are brought by the excretion of protons (H⁺), hydroxyl (OH⁻) or bicarbonate (HCO₃⁻) ions due to cation/anion imbalance in the plant, the evolution of CO₂ by respiration, and the excretion of low molecular weight organic acids. The form of N supply has a major role in the cation/anion uptake ratio and its subsequent effect on rhizosphere pH. As a consequence of cultivation shift from flooded paddy soil to aerobic soil, the dominant form of N taken up by rice roots is shifted from NH₄⁺ to NO₃⁻. Generally, to maintain electro neutrality within the plant cell, rhizosphere pH decreases when NH₄⁺ forms are used and increases when NO₃⁻ forms are used because of the release of H⁺ and OH⁻ or HCO₃⁻, respectively (Gao et al., 2002). Gao et al. (2006) conducted a field experiment related to bioavailability of Zn under aerobic as well as flooded conditions using six rice genotypes and reported that Zn concentration in rice plants at tillering stages was lower under aerobic condition than under flooded conditions. Rice varieties differ in their tolerance to Zn deficiency. Moreover, it was found that zinc application neither affected grain yield nor grain Zn content but significantly decreased Zn harvest index. So, development of rice cultivars with higher Zn efficiency and higher Zn harvest index seems a more promising and viable option than fertilization for increasing Zn content of the grain and overcoming Zn deficiency under aerobic conditions.

Under oxidized conditions, the production of phytosiderophores essential for chelating Fe²⁺ and making it available to rice plants is low. Fe deficiency can spring up in upland rice nurseries or during preflooding seedling establishment. Flooding the nursery area or fields can overcome such deficiency. Several-fold increase in DTPA-extractable Fe under submergence has been reported (Mandal and Das, 2002). However, DTPA-extractable Fe was significantly reduced when soil moisture was maintained at 0.2 or 1 bar (Pal et al., 2008) as compared to that at saturation. Singh et al. (2002) reported that DTPA extractable Fe in 0–15 cm layer was about 5 mg/kg soil in continuously submerged soil as compared to 2.1–2.5 mg/kg soil under different aerobic treatments. Rice varieties differ in their tolerance to Fe deficiency. For example, Pal et al. (2008) reported that cultivars CT6510- 24-1-2 (V1) and IR71525-19-1-1 (V2) performed better than IR36 (V3) and IR64 (V4) under aerobic system based on Fe²⁺ concentration, which is a better indicator of Fe deficiency or sufficiency and it was 68.8, 64.5, 50.7, and 43.3 mg/kg DM in V1, V2, V3, and V4 respectively.

Thus, from literatures it is evident that due to shift from flooding to aerobic system of rice cultivation, several factors that determine the availability of essential nutrients especially Fe and Zn, change thereby limiting the growth and productivity of rice. However, existence of genotypic differences for the Fe and Zn uptake under aerobic condition shows that genetic improvement seems to be a sustainable option than fertilization (Soil and foliar application) for enhancing the nutrient use efficiency and there by yield under aerobic condition.

(ii) Weeds: Weeds are the most yield-limiting constraint in aerobic rice production, responsible for about 50% in yield gap. Generally two to three weeding are required in aerobic rice needing about 190 man-days/ha. Also, some weeds such as Echinochloa sp. and Ischaemum sp. mimic rice during early growth stages (Leeper, 2010) and make hand weeding complicated. Herbicide recommendations are not that much effective and often lead to environmental contamination and development of herbicide resistance. Efforts are
therefore underway to develop weed competitive rice cultivars. Screening of rice cultivars for weed competitiveness under weed-free conditions using appropriate traits is a more practical indirect method. A three-year study at the IRRI, Philippines, with 40 aerobic and upland rice cultivars showed that vegetative vigor two weeks after sowing was the best trait for selection for their weed competitiveness. The other traits studied were plant height, productive tillers, days to flower, spikelets per panicle, filled grain percentage, grain yield, and harvest index (Zhao et al., 2006). The vegetative vigor at two weeks after seeding explained 87% of cultivar variation in weedy yield and 40% variation in weed biomass. In this study, cultivars BR144F-MR-6-0-0 and Way Rarem having an early vigor score of 7.2 and 7.1 (on 1–9 scale) had the lowest weed biomass of 128.2 and 128.9 g/m², respectively, and gave good yields of 3.28 and 3.04 t/ha, respectively.

(iii) Aerobic rice cultivars: New cultivars must be developed if growing rice like an irrigated upland crop is to be successful.

Evidence for the feasibility of aerobic rice comes from Brazil and Northern China. In China, the breeding program for aerobic rice was started in 1980s at the China Agricultural University (CAU), China Academy of Agricultural Sciences (CAAS), the Liaoning Province Academy of Agricultural Sciences (LPAS), and the Dandong Academy of Agricultural Sciences (DAAS). During 1980s and 1990s varieties, such as, Qinai, Hedda 77-2, Zhougyuan 1 & 2 and Han 72 were bred and released. However, due to some shortcomings such as vulnerability to rice blast, weak ability to emerge through the soil surface and low vegetative vigor limited their adoption (Huaqi et al., 2002). Later at CAU, a strong genetic recombination of lowland and upland rice varieties was started in 1984. This led to the development of special aerobic rice varieties called “Han Dao” (Such as HD 297, HD 277, HD 502) and field experiments began in 1990 to determine the yield potential. The experimental results showed that under aerobic conditions, the aerobic varieties HD 297 and HD 502 out yielded the lowland variety JD 305. With 470 mm water, HD 297 yielded 2.5 t/ha, HD 502 3.0 t/ha and JD 305 1.2 t/ha; with 644 mm water HD 502 and HD 297 yielded 5.3 and 4.7 t/ha, respectively while JD 305 yielded 4.2 t/ha. The water use efficiencies of aerobic varieties under aerobic conditions were 164-188 per cent higher than that of the lowland variety under lowland conditions (Wang and Tang, 2000). These varieties are currently grown on 140,000 ha in northern China. Replacing the traditional lowland rice in water shortage areas. Iron and Zinc deficiency symptoms were observed in aerobic rice in North China, 2 or 3 years after fields were shifted from flooded to aerobic conditions and therefore in China research is being focused on to improve nutrient use efficiency in addition to water use efficiency in aerobic rice varieties.

In Brazil, breeding programme on improvement of upland rice has resulted in improved aerobic rice varieties with a yield potential of up to 6 t/ha. These new varieties possess the characteristics of modern plant types: medium stature and tillering, resistance to lodging and short erect upper leaves. Farmers grow these varieties commercially on an estimated 2,50,000 ha under sprinkler irrigation (Guimaraes and Stone, 2000).

In tropical Asia, IRRI initiated its work on aerobic rice during 2001 targeting the tropical regions and developed few first generation aerobic rice lines by crossing drought-tolerant, highly weed-competitive upland cultivars with high-yielding and lowland-adapted varieties, and crossing two upland-adapted varieties, followed by evaluating and selecting progenies for early vegetative vigor, yield, and grain type under aerobic non-stressed conditions and for grain yield under aerobic severely drought-stressed conditions (Zhao et al., 2006). The promising first generation aerobic rice varieties developed by IRRI include IR55423-01 (named Apo) and UPLRI-5. Major QTLs for grain yield under aerobic conditions were also reported from IRRI in the genetic background of Apo and these QTLS can be introgressed into elite rice varieties through marker assisted back cross breeding.

In India, the research programmes on developing rice varieties suitable for aerobic condition started only recently. Central Rice Research Institute, Cuttack University of Agricultural Sciences, Bangalore and various State Agricultural Universities (SAUs) are working on the improvement of rice genotypes for aerobic condition through conventional as well as molecular breeding techniques.
**Conclusion:** Scarcity of water causes a shift from flooded to aerobic system of rice cultivation. But under aerobic system of rice cultivation, intermittent water limitation, non-availability of essential nutrients, especially iron and zinc and weed infestation results in yield reduction ranging between 15 and 40%. Developing suitable rice cultivars for aerobic conditions is essential to exploit the water saving potential of aerobic conditions. In Brazil and China, special aerobic rice varieties were developed and are currently planted on larger areas. In tropical Asia, IRRI initiated its work on aerobic rice during 2001 and had released first generation aerobic rice varieties. In India, so far genetic improvement of rice for aerobic conditions was given less attention when compared to lowland rice. But now, due to increasing demand for water, research programmes are being focused on to genetic improvement of rice for aerobic conditions and varieties are expected in near future.

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