Growing Rice with Less Water: Improving Productivity by Decreasing Water Demand

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Abstract Rice is a staple food for more than half of the global population. With the increasing population, the yield of rice must correspondingly increase to fulfill the requirement. Rice is cultivated worldwide in four different types of ecosystems, which are limited by the availability of irrigation water. However, water-limiting conditions negatively affect rice production; therefore, to enhance productivity under changing climatic conditions, improved cultivation practices and drought-tolerant cultivars/varieties are required. There are two basic approaches to cultivation: (1) plant based and (2) soil and irrigation based, which can be targeted for improving rice production. Crop plants primarily follow three mechanisms: drought escape, avoidance, and tolerance. Based on these mechanisms, different strategies are followed, which include cultivar selection based on yield stability under drought. Similarly, soil- and irrigation-based strategies consist of decreasing non-beneficial water depletions and water outflows, aerobic rice development, alternate wetting and drying, saturated soil culture, system of rice intensification, and sprinkler irrigation. Further strategies involve developing drought-tolerant cultivars through marker-assisted selection/pyramiding, genomic selection, QTL mapping, and other breeding and cultivation practices such as early planting to follow escape strategies and decreasing stand density to minimize competition with weeds. Similarly, the identification of drought-responsive genes and their manipulation will provide a technological solution to overcome drought stress. However, it was the Green Revolution that increased crop production. To maintain the balance, there is a need for another revolution to cope with the increasing demand.

Keywords Aerobic rice · Drought · Molecular breeding · *Oryza sativa* · Transgenic · Water deficit

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1 Introduction

More than 60% of the human population consumes rice (Joshi et al. 2018). An FAO report that considered rice production and growth of the human population in the past decade suggested the urgent need to increase rice production by 70% to fulfill upcoming demand by 2050 (FAO 2018; Schroeder et al. 2013). In view of this increased demand for rice production, an urgent need exists to study rice cultivation practices. Basically, rice cultivation is grouped into four ecosystems: irrigated (50% of the total rice grown), rainfed lowland (34%), rainfed upland (9%), and flood-prone (7%) (IRRI 2014). Cultivation under the irrigated rice ecosystem is the most productive and plays a significant role in meeting global food demand. However, irrigated rice itself is strongly affected by water availability, irrigation patterns, water quality, and the duration of water standing in the rice field during the growth period (Joshi et al. 2018). The rainfed ecosystem has a higher opportunity for yield improvement as it covers 43% of rice cultivation that still has limited yield potential. The most common factors that limit rice production in the rainfed ecosystem are irregular water supplies (i.e., severe drought, flood, and sometimes both in a single cropping season) and infertile soil due to its acidic or saline nature. Such conditions further complicate rice genetic improvement programs, which increases pressure on the irrigated ecosystem (He et al. 2020).

In recent years, changes in environmental conditions imposed multiple abiotic stresses that severely affect rice production in all ecosystems by strongly inhibiting plant growth and development (Joshi et al. 2020). According to one estimate, to produce 1 kg of rice, 2000–5000 L of water are required (Joshi et al. 2009; Caine et al. 2019). The increased competition of accelerated urbanization and industrial development further limit freshwater resources for rice production. Therefore, the need for “more rice with less water” is the need of the hour for global food security (Maneepitak et al. 2019; He et al. 2020). Thus, water availability is the key requirement for rice cultivation in each of the rice ecosystems. This forces us to develop new techniques of water management for rice cultivation that specifically improve production in different ecosystems (Carracelas et al. 2019). Further, water use can be managed either by cultivating water-stress-tolerant cultivars that can yield more under less water availability or by managing soil conditions suitable for growing rice under water-deficient conditions. Stress-tolerant cultivars can be identified from crop germplasm resources so that stress tolerance can be transferred into high-yielding cultivated varieties (Singh et al. 2015a,b; Mishra et al. 2016a, b). Aerobic rice (AR) is one of the promising rice cultivation systems for managing water and growing rice under water-limited conditions, thus decreasing water losses by 27–51% and increasing water productivity by 32–88% (Nie et al. 2007; Joshi et al. 2009). Aerobic rice varieties are usually grown in upland conditions in unpuddled soil in non-flooded conditions, that is, unsaturated (aerobic) soil with less water requirement (Bouman et al. 2006; Joshi and Kumar 2012). Under these conditions, the cultivation of high-yielding aerobic rice genotypes may help to save water. Other approaches that decrease water consumption are alternate wetting and

drying of the field; saturated soil culture (SSC) that relies on forming farming beds, separated by furrows in which a shallow depth of water is maintained; mid-season drainage; delayed flooding; and sprinkler irrigation. Keeping this in mind, the Indian Council of Agricultural Research-National Rice Research Institute (ICAR-NRRI), India, has released promising rice varieties for cultivation in varying rice ecosystems (https://crri.icar.gov.in/popular_var.pdf).

Water-limiting conditions are usually designated as drought and different plant species respond in different ways to cope with drought conditions: avoidance, tolerance, and escape (Turner 2003). These adaptation strategies include physiological and metabolic adjustment by plants to minimize damage caused by drought (IPCC 2001; Singh et al. 2015c). Escape is the capability of the plant to not reach drought conditions but instead complete the life cycle before drought onset in water-sufficient conditions (Boyer 1996; Joshi et al. 2014). This is of crucial importance as it is related to early establishment of the crop, inhibition of stomatal conductance, and water management. Thus, the goal is to have early flowering and maturity along with rapid germination and seedling establishment. Avoidance is a means to avoid the stress by maintaining ample water during the stress period (Bodner et al. 2015; Urban et al. 2017). Plants achieve this by changing the shape and decreasing the number and size of leaves. Plants also roll their leaves and change their orientation to decrease absorption of radiation and prevent water loss (Caine et al. 2019). Moreover, an increase in waxiness of leaves, root density, and deep rooting enables plants to uptake water from depth for sustaining themselves during adverse conditions (Ashraf et al. 2011; Joshi and Karan 2014). Cultivars that have these traits are suitable for the rainfed cropping system (Bodner et al. 2015; Korres et al. 2016). According to Levitt (1980), drought avoidance via an efficient water uptake methodology is the best method to achieve higher yield. Additionally, areas that are prone to frequent drought conditions should be cropped with cultivars that are early maturing and have high vigor (Gouache et al. 2012). The tolerance mechanism actually allows plants to survive and grow in stress conditions. This is done by maintaining turgor through osmoregulation, producing antioxidants, and accumulating compatible solutes (Joshi and Chinnusamy 2014).

2 Current Rice Cultivars/Varieties Grown Under Water-Limiting Conditions

Availability of water for irrigation is increasingly a limiting factor in attaining the full-yield potential among many crops (Boyer 1982). Various techniques have been devised and discovered to counteract the effects of water-limiting conditions and climate changes by using acquired plant adaptations. The appropriate choice of cultivar as per its adaptation to the rice ecosystem/local environment is important as different varieties show different mechanisms to cope with drought (Turner 2003). A field experiment using two rice genotypes, Hanyou 113 (HY113) and Yangliangyou

6 (YLY6), under flooding and drought stress revealed that drought stress at the reproductive stage strongly affects physiological traits, yield, and grain quality (Yang et al. 2019). IRRI has successfully developed and released 17 high-yielding drought-tolerant rice varieties, which include Sahod Ulan and Katihan (Philippines), Hardinath and Sookha Dhan (Nepal), Sahbhagi Dhan (India), BRRI dhan (Bangladesh), Inpago LIPI Go 1/2 (Indonesia), M'ZIVA (Mozambique), and UPIA3 (Nigeria) (Kumar et al. 2014). In India, Sahbhagi Dhan was reported to produce 4 t/ha under normal conditions and 1–2 t/ha under severe drought conditions. Because of its early maturity (105 days) and low irrigation requirements, farmers can save up to USD 60 per crop (Basu et al. 2017). Similarly, in Nepal, drought-tolerant cultivar Sookha Dhan 2 showed higher yield from an altitude of 1000–1600 masl (Dhakal et al. 2020). Further, ICAR-NRRI has developed and released drought-tolerant rice cultivar DRR-Dhan 45, which is moderately resistant to major diseases and pests such as rice tungro viruses, sheath rot, and blast, with average yield of 6 t/ha (Nirmala et al. 2016).

3 Existing Rice Cultivation Practices Under Water-Deficit Conditions

Farmers practice a traditional way of cultivation and selection of cultivars as per their natural adaptations toward changes in environmental conditions (Gala Bijl and Fisher 2011). However, with rice cultivation, emphasis has been given to the development of rice cultivation techniques that result in a lot of technological options for cultivation to enhance production under water-limiting conditions (Fig. 1). A cumulative approach of water management and cultivation of high-yielding varieties that performed well under water-limiting conditions was supposed to diminish the yield penalty. Therefore, water management practices, including short-term, long-term, and anticipatory phenological adaptation measures, are required before assessing the impact of water-limiting conditions, and they usually aim at mitigating effects (Nguyen 2005; IPCC 2007). A study on phenological and water-saving adaptation strategies of crop plants showing higher yield stability under water-limiting conditions has further proved the utility of cumulative approaches (Bodner et al. 2015).

3.1 Plant-Based Strategies

3.1.1 Selection of Cultivars/Varieties

The right choice of cultivar plays a significant role in rice cultivation under less water because of specificity of the tolerance mechanism of a cultivar to drought: tolerance, avoidance, and escape. Cultivar selection basically depends on

Fig. 1 Different strategies to improve rice productivity by decreasing water demand

demography and availability of water for irrigation. Following an escape strategy, plants complete their life cycle before drought onset in water-insufficient conditions (Boyer 1996). Cultivars having early flowering and maturity date and also rapid germination and establishment time completed their life cycle early and were therefore selected for cultivation in rainfed upland, lowland, and typhoon-prone coastal areas (Fukai et al. 1999). Areas that are prone to frequent drought conditions should be cropped with cultivars that are early maturing and have high vigor (Gouache et al. 2012; Bodner et al. 2015). Similarly, cultivars adapted for drought avoidance traits such as decreasing size and number of leaves, leaf rolling, and an increase in waxiness of leaves, density of root, and deep rooting are suitable for cropping in the rainfed ecosystem (Farooq et al. 2009; Bodner et al. 2015; Korres et al. 2016). Plants having a tolerance mechanism maintain turgor pressure through osmotic adjustment via generating osmolytes and osmoprotectant and producing antioxidants. In addition, the development of screening tools to identify drought stress tolerance at the seedling stage is crucial for developing rice cultivars suitable for water-limited environments. Thus, 100 *tropical japonica* rice genotypes were studied under pot conditions for their drought tolerance and a cumulative drought stress response index (CDSRI) was developed by combining individual response indices of all the varieties that were found to be important for identifying tolerant cultivars for early-season drought (Lone et al. 2019). Similarly, taking 15 rice cultivars commonly grown in Mississippi (USA), early-season drought-tolerant cultivars were selected by analyzing total drought response index (TDRI) (Singh et al. 2017).

3.1.2 Date of Planting

Planting date is related to the drought escape mechanism so as to escape drought conditions and it is the most appropriate method of escape (Ding et al. 2020). Thus, to avoid drought, optimization of sowing time as per water availability and demand is crucial. Three reasons were found to be critical for early sowing in dry environments (Bodner et al. 2015):

1. Climatic variations in evapotranspiration improve water-use efficiency of early-planted cultivars because most of the developmental stages have to face decreased water potential gradients.
2. Early sowing shifts sensitive stages (germination and reproductive stages) to periods of better water availability.
3. Early-sown cultivars develop deeper roots and facilitate the drought avoidance mechanism.

For long-term climatic changes, early sowing is a suitable solution (Ding et al. 2017) because of the availability of ample amounts of water and nutrients that will improve canopy development, yield, and biomass production. In contrast, an increase in canopy area will increase evapotranspiration (Lin et al. 2020). Therefore, variations in biomass production per unit transpiration through adjustments in planting dates will be beneficial for drought tolerance or drought escape. Although early planting could enhance spikelet sterility caused by high temperatures (Jagadish et al. 2015), by using early-maturing cultivars, both a drought and heat stress escape strategy will be a beneficial approach (Mukamuhirwa et al. 2019).

3.1.3 Decreased Stand Density

A decrease in stand density focuses on a decrease in intraspecific competition and improved water availability for a single plant and thus is a measure related to water saving. Although decreased stand density also relates to higher evapotranspiration, it is beneficial under certain conditions. An increase in soil evaporation by decreasing plant density and/or widening row spacing depends on the prevalence of rainfall and is more during intermittent drought than in a prolonged dry span. Besides evaporation, decreased radiation interception due to scattered stands might diminish growth and increase weed competition with crop plants such as wheat (Chen et al. 2008), rice (Rees and Khodabaks 1994), maize (Barbieri et al. 2012), barley (McKenzie et al. 2005), sugar beet (Ehlers and Goss 2016), and sorghum (Buah and Mwinkaara 2009). These have been investigated under different conditions and high yield has been observed with low stand density.

3.2 *Soil- and Irrigation-Based Strategies*

Environmental changes will influence water accessibility, especially in rice in zones where water is scarce. Expanded high-temperature environments diminish rice yield amid the dry season when prevention measures are lacking. Water system alterations or improvement of appropriate water system frameworks allow water reserves while decreasing the yield penalty (Krishnan et al. 2011). The existing water-saving technologies, for example, the alternate wetting and drying (AWD) water system, SSC, and aerobic rice system, appear to be the most appropriate advances in current rice research work (Joshi et al. 2018). With a deprived water system and poor administration, rice production is more affected by climatic vagaries, especially in tropical countries (Wassmann and Dobermann 2014). Improving technologies for increasing water-use efficiency will provide long-term economic as well as environmental benefits. This would also decrease soil salinization problems that arise from irrigation (Wang et al. 2016).

3.2.1 *Alternate Wetting and Drying*

As indicated by Tuong (1999), by just considering evapotranspiration, 500–2000 kg of water are required to produce 1 kg of rice, which gives 33–50% water profitability (Bouman and Tuong 2001). The AWD technique primarily relies on water management by alternately applying water in either flooded or non-flooded conditions (Maneejitak et al. 2019). This alteration in watering the field has been determined by a fixed number of non-flooded days, extent of soil potential, appearance of cracks on the soil surface, symptoms shown by plants, and a drop in water level below the soil surface (Pascual and Wang 2017; Sriphirom et al. 2019). Further, in the AWD system, water is connected to non-flooded soil for a few days after flooding recedes (Bouman et al. 2007). Soil type also influences the measure of water reserves through AWD in contrast to customary flooded rice. In loamy and sandy soils with deep groundwater tables, water input decreases by using AWD, with a 20% yield decrease, in contrast to waterlogged cropping (Singh et al. 2002). However, in soils with shallow groundwater tables, water input diminishes by 15–30%, accompanied by a noteworthy yield decrease (Carracelas et al. 2019). Grain production in AWD is usually lower than in flooded rice. However, water-use efficiency (the estimation of aggregate water used) in AWD is higher, based on decreased water inputs (62%) and decreased yield (25%) (Bouman et al. 2007; Wang et al. 2016). This shows the higher efficiency of AWD technology in comparison to persistent overflowed rice production in connection with water use per unit that results in a 24.6% increase in income from rice cultivation (Uddin and Dhar 2020). In addition to decreased water loss, AWD has been reported to decrease methane emissions from rice fields and decrease heavy metal accumulation in rice grain (Carrijo et al. 2018; Wang et al. 2019; He et al. 2020).

3.2.2 Saturated Soil Culture

In this system, soil is kept soaked as much as could reasonably be expected to bring about a diminished hydraulic head to flooding. This diminishes water loss by decreasing leakage and permeation streams (Borrell et al. 1997; Bouman et al. 2007). This shallow-water system of around 1 cm of water profoundly diminishes water consumption from 10 to 25% in comparison with continuous flooding (Bouman and Tuong 2001). This framework, in light of information from Tabbal et al. (2002), transfers the superiority of wet-seeded rice to transplanted rice with decreased rice yield under continuous flooding (i.e., 4% vs. 10%). Therefore, in both wet-seeded and transplanted rice, the water profitability under SSC was found to be higher than that in consistently flooded rice, in addition to the cost effectiveness for farmers' acceptability (Kima et al. 2014).

3.2.3 Aerobic Rice Development

Aerobic rice development is used to decrease water needs since the rice is grown as an upland harvest with optimum yield and a supplementary water system just when precipitation is inadequate (Joshi et al. 2018). In this system, rice cultivars were sown in non-puddled and unsaturated (vigorous) soils (Bouman et al. 2007). Vigorous rice cultivars have been achieved by consolidating the positive attributes of upland rice with those of high-yielding flooded rice (Atlin et al. 2006). During the mid- to late 1990s, early-maturing, oxygen-consuming, nitrogen-efficient, and high-yielding aerobic rice cultivars were released, such as Han Dao 502, Han Dao 297, and Han Dao 277 (Yang et al. 2005; Joshi et al. 2018). These new cultivars have 50–70% less water consumption than flooded rice due to their more extended roots that encourage water retention and enhance air dissemination (Mitin 2009). Under field conditions, these aerobic cultivars produce from 4.7–6.6 t/ha to 8.0–8.8 t/ha under flooded conditions (Xue et al. 2008). In addition, rice cultivars bred for the aerobic system must also be bred for competitive ability with weeds because of enhanced weed problems as soon as flooding is removed (Korres et al. 2016). Thus, the traits related to water and nutrient acquisition that affect weed-suppressive ability of the crop include root surface area, water uptake rate, root length, and root density (Korres et al. 2016).

3.2.4 Decreasing Non-beneficial Water Depletions and Water Outflows

A decrease in evaporation during different stages of development is achieved by early canopy closure via either manipulating crop density or selecting rice cultivars with good seedling vigor (Gouache et al. 2012; Bodner et al. 2015). These measures also increase the competitive ability of the crop by decreasing transpiration from weeds (Korres et al. 2016). In addition, other methods to control weeds include using herbicides, manual or mechanical weeding, timely flooding, and land leveling,

which can help to diminish non-beneficial water losses that occur due to transpiration by weeds (Rodenburg et al. 2011). Soil mulching is also an effective approach to increase water productivity and decrease water inputs in rice, especially under non-saturated aerobic soil conditions (Dittert et al. 2002). Puddling in clay soils (Tuong et al. 2005) or soil compaction in sandy-loamy soils with clay content greater than 5% or shallow tillage before flooding was reported to be beneficial in decreasing water outflows (Cabangon and Tuong 2000; Tuong et al. 2005).

3.2.5 System of Rice Intensification

To increase rice productivity, a climate-shrewd agroecological method is required to increase rice yield by altering water, soil, plant, and supplement management. The SRI philosophy depends on the following four fundamental rules that are connected with each other: early, snappy, and sound plant foundation; decreased density of plants; upgraded soil conditions through augmentation with organic supplements; and controlled and decreased application of water (Uphoff 2004; SRI-Rice 2010). In light of these standards, farmers can adjust prescribed SRI practices according to their agroecological and financial conditions. Adjustments are frequently embraced to handle changing soil conditions, climate designs, water control, work accessibility, access to natural resources, and the choice to completely depend on organic farming (Uddin and Dhar 2020). Notwithstanding flooded rice, SRI standards have been connected to rainfed rice and to different harvests, for example, wheat, finger millet, sugarcane, beets, and teff, demonstrating expanded profitability over current old cropping practices. At the point when SRI standards are connected to different products, we allude to it as the system of crop intensification or SCI. The advantages of SRI included up to a 90% decrease in seed requirement, 20–100% or more expanded yield, and up to half water reserves. SRI standards and practices have been developed for rainfed rice and also for different harvests, with yield increments and related financial advantages (Duttarganvi et al. 2014).

3.2.6 Sprinkler Irrigation

The majority of cultivated rice across the globe is grown under flooded conditions, through which a huge amount of water is lost via deep percolation, seepage, surface runoff, and evapotranspiration (Vories et al. 2013; Materu et al. 2018). Among the various techniques developed for water-saving irrigation, mechanized sprinkler irrigation systems are gaining attention among farmers in several countries because of easy management of irrigation combined with improved water-use efficiency and enhanced productivity (Kahlowan et al. 2007; Spanu et al. 2009; Vories et al. 2017; Kar et al. 2018; Mandal et al. 2019; Pinto et al. 2020). In comparison to 1168 mm in flooded rice, a total depth of 414 mm can be achieved by sprinkler irrigation with a 20–50% decrease in water consumption (Vories et al. 2013; Pinto et al. 2016; Kumar et al. 2018). Additionally, sprinkler irrigation enables farmers to adopt soil conservation techniques such as no-till farming and crop rotation (Pinto et al. 2020).

4 Molecular Breeding for Rice Improvement

To attain global food security, a promising approach is to cope with drought by developing drought-tolerant cultivars (Xiao et al. 2009). However, drought tolerance is a complex trait that involves changes at developmental, physiological, biochemical, and molecular levels (Joshi and Karan 2014). These changes involve alterations in photosynthesis, osmotic adjustment, guard cell regulation, root growth, and synthesis of specific proteins and antioxidants. In addition, breeders can attempt to improve yield through improved harvest indices, manipulating transpiration rate, and decreasing non-beneficial depletions (Tuong 1999; Bennett 2003). In this regard, considerable progress has been made and several QTLs (Quantitative Trait Loci) for drought-related traits that lead to improved grain yield under water-limiting conditions have been identified and transferred into suitable varieties through marker-assisted breeding (MAB). However, most of the studies were conducted on biparental or multiparental populations that use only allelic variations present within the selected parents. In addition, there is limited exploration of genetic resources in identifying novel QTLs regulating drought-related traits (Kumar et al. 2014; Pascual et al. 2016).

4.1 QTL Mapping

QTL mapping is the genetic association between the genotypic constituents of a population and the trait of interest. Therefore, to map a QTL, it is mandatory to develop a mapping population, genotype it, and make a linkage map out of it. Mapped QTLs need to be identified by their robustness and contribution toward the trait of interest by estimating an LOD score and phenotypic variation (PV). PV of more than 10% was considered as a major QTL and less than that considered as a minor QTL. Much progress has already been made toward identifying drought-related traits and associated genetic factors, that is, QTLs/genes that demarcate tolerant rice cultivars. Subsequently, identified genetic factors have been transferred into high-yielding drought-susceptible rice varieties. Using rice genetic resources, different QTLs targeting major drought-related traits, including yield under water-limiting conditions, deep rooting, osmotic- and dehydration-responsive traits, etc., have been identified and transferred. For drought tolerance, several QTLs have been identified, although only a few have a significant effect on rice under water-limited conditions (Table 1). One of the QTLs for deep rooting has been identified from japonica cultivar Kinandang Pantong (KP) (Uga et al. 2013). Multiple QTLs related to yield under water-limiting conditions have been identified in different *indica* cultivars and wild progenitors of cultivated rice *Oryza rufipogon*. Bernier et al. (2007) identified a QTL on chromosome 12 (*Qtl12.1*) that accounted for about 50% of the genetic variation and functionally reported an increased water uptake of plants under drought stress. QTL *qDTY3.1* had been identified from a cross between

Table 1 Drought tolerance QTLs mapped and used for rice breeding programs

QTL/gene	QTL/gene	Identification method	Cultivar/variety group	References
<i>DRO1</i>	Deep rooting	Fine mapping	Kinandang Patong (KP)/ <i>japonica</i>	Uga et al. (2011, 2013)
<i>DRO2</i>	Deep rooting	Fine mapping	KP/ <i>japonica</i>	Uga et al. (2013)
<i>DRO3</i>	Deep rooting	Fine mapping	KP/ <i>japonica</i>	Uga et al. (2015)
<i>QTL2</i> , 9, and 11	Controlling root traits	Mapping	Azucena/ <i>japonica</i>	Steele et al. (2006, 2007, 2013)
<i>qtl12.1</i>	Plant water uptake	Mapping	Way Rarem	Bernier et al. (2009)
<i>qDTY2.3</i> and <i>qDTY3.2</i>	Grain yield under drought	Mapping	Vandana/cross between <i>indica</i> and cross product of <i>japonica</i> and <i>indica</i>	Dixit et al. (2012)
<i>qDTY1.1</i>	Grain yield under drought	Mapping	N22/ <i>aus</i>	Vikram et al. (2011)
<i>qDTY2.2</i> , <i>qDTY4.1</i> , <i>qDTY9.1</i> , and <i>qDTY10.1</i>	Grain yield under drought	Mapping	Aday Sel	Swamy et al. (2013)
<i>qDTY1.1</i>	Grain yield under drought	Mapping	Dhagaddeshi	Ghimire et al. (2012)
<i>qDTY2.1</i> and <i>qDTY3.1</i>	Grain yield in lowland drought stress	Mapping	Apo (IR55423-01)/ <i>indica</i>	Venuprasad et al. (2009)
Multiple root traits	Multiple root traits		Yueful/ <i>japonica</i>	Li et al. (2005)
Rooting			Moroberekan/ <i>japonica</i>	Champoux et al. (1995)
QTL (osmotic adjustment)	QTL (osmotic adjustment)		Co39/ <i>indica</i>	Lilley et al. (1996)
Multiple QTLs	Multiple QTLs		Aus 276/ <i>aus</i>	Sandhu et al. (2014)
Multiple QTLs	Multiple QTLs		<i>O. rufipogon</i> /wild	Zhou et al. (2009)
Polygenes/multiple genes	Polygenes/multiple genes		<i>O. rufipogon</i> /wild	Hu et al. (2011)
<i>qRL6.1</i>	Root length			Gowda et al. (2011)

tolerant variety Apo and susceptible variety Swarna showing a large effect on drought tolerance (Venuprasad et al. 2009). Different studies identified multiple DTY QTLs from different donor rice cultivars such as Dhagaddeshi, Apo, N22, Aday Sel, Way Rarem, etc., and incorporated them into rice breeding programs for improving drought tolerance in rice (Sandhu and Kumar 2017).

4.2 *Marker-Assisted Selection*

Marker-assisted selection (MAS) is a practice to substitute phenotypic screening by using molecular markers linked to particular loci. MAS precisely isolates the desired genotype at particular marker loci from a population without being a phenotype (Qing et al. 2019). MAS could be applied in various ways for crop improvement programs such as the marker-assisted evaluation of breeding material, early-generation selection, marker-assisted backcross breeding, gene pyramiding, and combined MAS (Collard and Mackill 2008). Kumar et al. (2018) used early-generation selection by combining both phenotyping and genotyping for the selection of drought-tolerant progenies and subsequently incorporated them into their breeding programs.

4.3 *Marker-Assisted Backcrossing*

Marker-assisted backcrossing (MABC) is an efficient genetic method to transfer a locus controlling a trait of interest from wild relatives, landraces, and known trait-specific genes from a genetic material into desired cultivars, called recurrent parents, without altering their essential characteristics (Dixit et al. 2017). The MABC scheme includes foreground selection, recombinant selection, and background selection. Integrating linkage map information with a QTL map helps span the markers in the target locus. Foreground selection was performed with peak markers, which assisted in the selection of a linked gene/QTL in the progenies while flanking markers of the target locus were used for recombinant selection. Foreground selection was performed in each filial generation. Recombinant selection was performed to minimize linkage drag and decrease the size of the target locus containing the gene of interest in an elite background (Collard and Mackill 2008). Background selection must be performed at later stages of breeding programs to minimize cost and labor. After that, the BC_2F_2 or BC_3 generation should be selected for background selection (Ab-Jalil et al. 2018). This method is used to validate the function of QTLs from identified genotypes by transferring them into different genetic backgrounds (Ha et al. 2016). MABC is employed for transferring QTLs for different drought stress-related traits such as qDTYs for yield under drought conditions (Kumar et al. 2014); *DRO1*, *DRO2*, and *DRO3* for deep rooting (Uga et al. 2011, 2013, 2015); *qRL6.1* for root length (Gowda et al. 2011); and *QTL12.1* for plant water uptake (Bernier et al. 2009).

4.4 *Marker-Assisted Pyramiding*

Several morphological and physiological characters have been reported that contributed to drought tolerance and each of the traits can be controlled by a QTL (Sandhu et al. 2019). Moreover, individual QTLs can contribute to yield under

drought stress. Several important traits controlling drought tolerance are root traits, plant morphology, and yield under drought stress, and QTLs for these have been mapped (Muthu et al. 2020). Pyramiding of QTLs/genes is a widely followed approach in disease resistance breeding. However, polygenic traits governed by more than one gene within the identified QTLs are complex to integrate. A significant amount of work has to be done for pyramiding multiple QTLs. A suitable approach for integrating multiple QTLs is equally important. Sometimes, integrated multiple QTLs may not work as they work independently. Nevertheless, the approach of gene/QTL integration depends on the number of QTLs to be integrated, the presence of QTLs in the same genetic backgrounds or different ones, the distance between the QTL and flanking marker, the filial stage, and the recovered recurrent parent genome (Shamsudin et al. 2016). Less breeding time is required if the QTLs to be integrated are present in the same genetic background in the advanced filial generation that recovered a higher proportion of recurrent parent genome. Genetic parameters such as interaction between alleles, within QTLs, and with the genetic background; pleiotropic effect of genes; and linkage drag of the introgressed loci need to be addressed (Kumar et al. 2018). For analyzing positive effects of alleles and other genetic effects, a large number of progenies need to be phenotyped and genotyped, which may correspondingly increase with the complexity of the trait (Kumar et al. 2018). Still, some success stories are present for MAP for drought, including DTY QTLs $qDTY_{2.2} + qDTY_{4.1}$ (Swamy et al. 2013); $qDTY_{12.1} + qDTY_{3.1}$ (Shamsudin et al. 2016); $qDTY_{3.2}$ and $qDTY_{12.1}$ (Dixit et al. 2017); $qDTY_{2.2}$, $qDTY_{3.1}$, and $qDTY_{12.1}$ (Shamsudin et al. 2016); and root QTLs for drought tolerance, qRT_{6-2} , qRT_{11-7} , qRT_{6-2} , and qRT_{19-1+7} (Selvi et al. 2015).

4.5 Marker-Assisted Recurrent Selection

Marker-assisted recurrent selection (MARS) is basically increasing the frequency of beneficial alleles with additive and small individual effects (Bankole et al. 2017). Selection cycles started with parental selection (called the C_0 cycle) and after that three to four rounds of recurrent selection. Parental selection can be carried out through genomic selection by calculating the genomic estimated breeding value (GEBV) across all the lines in the original populations (C_0). The best linear unbiased predictor helps in predicting GEBV. Lines with the highest GEBVs were planted and intercrossed. Thereafter, subsequent recombinant selection cycles (C_1 to C_3) were performed based on recombination of selected associated markers (Grenier et al. 2015; Sevanthi et al. 2019). While performing MARS, there is an increase in the frequency of favorable alleles and this minimizes genetic drift (Bankole et al. 2017). Important points to be considered while performing MARS are allelic interaction, genotype by environment interactions, functions of alleles in different genetic backgrounds, and cost and time duration of performing MARS. In rice, MARS is employed for incorporating DTY QTLs ($qDTY_{1.1}$, $qDTY_{2.1}$, $qDTY_{3.1}$, and $qDTY_{11.1}$) into a Samba Mahsuri background (Sandhu et al. 2018).

4.6 Genomic Selection

Genomic selection (GS) is a next-generation breeding strategy that ensures speedy breeding and selection of desired genotypes for cultivar improvement. GS is completed in two phases: training phase and breeding phase (Nakaya and Isobe 2012). The training population is used to predict genomic values; therefore, it is genotyped as well as phenotyped. Based on this information, a breeding model is developed to calculate the GEBVs of individuals in the testing population, which is only genotyped. Based on the GEBVs, progenies are selected, thus increasing the proportion of high-performing progenies in a population and increasing the breeding gain (Shikha et al. 2017). GS has a greater relevance in cases of drought as its phenotyping demands extensive field screening, cost, and labor (Cabrera-Bosquet et al. 2012). While performing GS, genetic heterozygosity, and genotype $\times$ genotype and genotype $\times$ environment interaction may affect the genomic prediction. There is also a need for a model-based prediction of GE and GG interactions. For complex traits such as drought, reaction norm model GEBV has greater accuracy than conventional models (Mulder 2016). Similarly, molecular marker-based predictions of crop traits are more accurate than pedigree-based predictions (Crossa 2012).

5 Transgenic Strategies

Transgenic studies have opened the door to the development of useful varieties that are superior in various traits. Because of a complex trait, different gene families are supposed to be upregulated or downregulated during drought stress. These genes belong to transcription factors, kinases, late embryogenesis abundant (LEA) proteins, osmoprotectants, and phytohormone families, and their transfer in different genotypes showed improved drought tolerance (Joshi et al. 2016). NAC family genes are responsive under drought stress (Nakashima et al. 2012) and overexpression of *OsNAC9* showed drought tolerance in transgenic plants in field trials (Redillas et al. 2012). Other transcription factors such as *AbEDT1* (Yu et al. 2016), *SNAC1*, *SNAC2*, and *OsNCED3* were upregulated in transgenic rice plants in response to drought stress.

Kinases represent a diversely fractioning gene family and enhanced drought tolerance was reported in transgenic plants overexpressing calcium-dependent protein kinase, including *OsCPK4* (Campo et al. 2014), *OsCDPK7* (Saijo et al. 2000), and *DcaCIPK9*, -14, and -16 (Wan et al. 2019). Overexpression of *OsCIPK12* showed tolerance by increasing the accumulation of osmolytes such as proline and soluble sugars. Receptor-like kinase (RLK) *OsSIK1* aided in drought tolerance in transgenic rice plants by an increased accumulation of peroxidase, catalase, and superoxide dismutase and decreased stomatal density and decreased accumulation of H_2O_2 (Ouyang et al. 2010). Another enzyme of the RLK family, *SIK2*, also showed drought tolerance in transgenic rice plants (Chen et al. 2013).

LEA proteins are stress inducible and play a significant role in protection under stress conditions (Minh et al. 2019). Reports show enhanced tolerance of drought in transgenic plants overexpressing *OsLEA3-1* or *OsLEA3-2* (Xiao et al. 2007; Duan and Cai 2012). SNAC2 protein binds to the *OsOAT* promoter expressing ornithine δ -aminotransferase (You et al. 2012) and overexpression of the *OsOAT* gene enhanced the activity of δ -OAT in transgenic rice. This increased glutathione, proline, and ROS-scavenging enzyme activity, resulting in drought tolerance. Similarly, overexpression of the trehalose-6-phosphate synthase (*OsTPS1*) gene expressing an enzyme in trehalose biosynthesis showed improved drought tolerance in transgenic rice (Li et al. 2011). Using a fusion gene from *Escherichia coli* coding for trehalose-6-phosphate synthase/phosphatase under the control of an ABA-inducible promoter, we generated marker-free, high-yielding transgenic rice (in an IR64 background) that can tolerate high pH (~9.9), high EC (~10.0 dS/m), and severe drought (30–35% soil moisture content) (Joshi et al. 2020). Enhanced tolerance was observed in transgenic rice overexpressing the *OsPYL/RCA5* gene. Expression of stress-responsive genes was increased, resulting in enhanced drought tolerance (Kim et al. 2010). The isopentenyltransferase gene (*IPT*), involved in cytokinin synthesis, under control of a SAPK promoter, exhibited changes in the expression of genes involved in hormone homeostasis and resource mobilization, delay in stress response, and enhanced drought tolerance (Peleg et al. 2011). Further, in the expression analysis of *OsM4* and *OsMB11* genes, we found these genes to be highly expressed under drought and salinity stress conditions (Kushwaha et al. 2016). We also reported that transgenic rice constitutively overexpressing *SaADF2* showed higher growth, relative water content, photosynthesis, and yield under drought conditions than the wild type under drought stress conditions (Sengupta et al. 2019).

6 Future Prospects

The current challenge is a sustainable increase in rice production corresponding to demand. The development of high-yielding varieties resistant to diseases and insects and tolerant of major abiotic stresses is essential for producing enough rice under irrigated habitats. However, production is limited in upland and rainfed areas and also under limited water availability. It was demonstrated earlier that farmers in drought-prone areas accept the decrease in yield variability offered by new stress-tolerant cultivars, and would be willing to pay a significant premium for these traits (Arora et al. 2019). Therefore, it is important to work concurrently on both aspects: the development of technology related to crop management and improvement of rice varieties for yield under adverse conditions. Climate changes further complicate the conditions for rice cultivation in these areas. This leads to intermittent rainfall, enhanced flash flooding, and sporadic drought, which adversely affect cultivated soil. Secondary adverse effects on crop production due to climatic fluctuation are changes in soil stature, enhanced soil salinity, and loss of genetic diversity. Therefore,

to mitigate these effects, researchers seek to exploit existing genetic resources. In the context of rice, ample germplasm accessions belong to different species and have been conserved *ex situ* and more efforts are in progress. Improvement strategies such as marker-assisted selection, marker-assisted backcrossing, marker-assisted pyramiding, marker-assisted recurrent selection, and genomic selection rely on QTL mapping, which itself relies on pre-breeding experiments. Pre-breeding strategies for the selection of cultivars to incorporate into breeding cycles are major components for succeeding in breeding programs. Further, transgenic approaches have been applied for functional validation of genes, improving quality traits, and developing resistant and tolerant cultivars. Thus, the development of rice cultivars with improved water-use efficiency will offer significant economic and environmental benefits toward the achievement of the Sustainable Development Goals.

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