Review Article

Journal of Scientific Enquiry
Vol: 2(2) , Pages:101-108

Drought response in rice - A brief review

Anirneeta De [1], Avishek Dey [2], Subrata Raha [3]* and Dipak Kumar Kar [4]*

1,3 Department of Botany, Sidho-Kanho-Birsha University, Purulia, W.B. – 723104, India.

2 Asst. Prof., Dept. of Botany, R. C. College, Purulia. W.B.- 723151, India.

4 Vice-chancellor, Sidho-Kanho-Birsha University, Purulia, W.B. – 723104, India.

Received: 26.11.2022; accepted: 28.12.2022; published online: 31.12.2022

Abstract

Rice is one of the most highly consumed cereals in the world and a reduction in its yield as a consequence of climate change has threatened global food security. Drought caused due to changes in the weather pattern is common. In the last few decades, extensive research in this context has been done for screening drought-tolerant rice germplasms but little success was there. More studies are needed to improve the screening method which can be achieved by understanding the fundamental mechanism of rice lines to tolerate water stress. Once true drought-tolerant germplasms are selected, they can be used in several breeding programs as the donor parent. Instead of conventional breeding, a molecular approach can be employed to enhance the process. Different types of plant response in water deficit conditions should be taken into consideration and should closely be investigated through various experiments.

Keywords: Rice, Breeding Approach, Response, Drought-tolerant

1. Introduction

Rice (*Oryza sativa*) is one of the world's most widely consumed staple food, especially for the people of South and Southeastern Asia [1]. The surging population and rapid industrialization have left a very small amount of arable land for cultivation. Climate change has influenced several environmental factors including temperature, and precipitation which have created havoc deviations in the weather pattern leading to various abiotic stress effects on plants [3]. Amongst these stress conditions, drought is one of the major threats to agriculture and it has also led to massive crop loss in several parts of the world [4]. According to Panda et al., 2021 more than 1/3 of the world's total cultivated area is affected by drought stress [2]. In Asia, 3.4 X 10^7 hm^2 and 8 X 10^6 hm^2 areas of rain-fed lowland and upland ecosystems respectively are heavily exposed to drought stress [5]. With all these climatic impediments and environmental issues where the demand for food is ever-increasing, there is an urgent need to develop varieties that have drought tolerance to improve rice productivity [4]. Several attempts have been made to incorporate the quality of drought tolerance in high-yielding varieties through breeding or hybridization programs, but the result has not been that striking as there are few limitations [5]. Firstly, there is a lack of appropriate screening methods for drought tolerance [6]. It is very tough to manifest a proper method of screening because the effects of drought on plants vary with the duration and severity of water stress and the phenological age of plants [7]. Another limitation would be the deficiency of true drought-tolerant varieties [2, 4]. As a result, no such line has been found that can act as a proper donor for the drought-tolerant trait in breeding programs. In this review, we will focus on the screening of germplasms done so far, their molecular characterization, breeding approaches that can be taken up for varietal development, different mechanisms followed by plants to survive the drought condition, and the morpho-physiological changes during drought stress.

2. Screening and molecular characterization of drought-tolerant germplasms:

In the last few decades, several screenings for drought tolerance have been carried out. IRRI (International Rice Research Institute), Philippines screened near about 1000 accessions collected from 47 countries all over the world [6]. A total of 65 germplasms that originated from 13 different countries were accepted as drought-tolerant lines. The screening was simply based on grain yield. Lines showing higher yield in any crop season were selected as drought tolerant [8]. Out of the 65 accessions, 48 originated from Bangladesh and India and the rest were from 11 different countries; 4 accessions from Sri Lanka, 3 from the Philippines, 2 from Vietnam, and one accession each from Afghanistan, China, Liberia, Malaysia, Nepal, Thailand, Pakistan, and USA [6]. Some popular drought-tolerant varieties like Dular, Shada Shaita, Kataktara, Da2, and DA28

DOI: https://doi.org/10.54280/jse.222215

that were developed through breeding programs are still cultivated in considerable areas of Bangladesh [8, 9].

Molecular study of these lines is crucial to discover the QTLs associated with drought tolerance mechanisms and using these lines in crop improvement programs [2, 6]. After extensive research, many QTLs linked to different physiological and morphological traits under drought stress have been identified and have been used extensively for the selection of tolerant rice genotypes [10, 11, 12]. Considering yield as the decisive trait, a further investigation aimed at mapping QTLs for grain yield of rice under drought stress. QTLs identified in rice for drought tolerance are mostly from non-elite genotypes [2, 4]. Drought grain yield QTLs having large effects identified so far are listed below in Table 1.

QTL	Associated trait	References
qDTY1.1	Grain yield	Vikram et al., 2011 [13], Ghimire et al., 2012 [14]
qDTY2.1	Grain yield	Venuprasad et al., 2009 [15]
qDTY2.2	Grain yield	Swamy et al., 2013 [16]
qDTY3.1	Grain yield	Dixit et al., 2014 [17]
qDTY3.2	Grain yield	Vikram et al., 2011 [13], Yadaw et al., 2013 [18]
qDTY6.1	Grain yield	Dixit et al., 2014 [17]
qDTY9.1	Grain yield	Swamy et al., 2013 [16]
qDTY12.1	Grain yield	Bernier et al., 2007 [19]
qDLR8.1	Leaf rolling	Dixit et al., 2012 [20]
qLR9.1	Leaf rolling	Barik et al., 2019 [21]
qDTR8	Transpiration	Ramchander et al., 2016 [22]
qLD9.1	Leaf drying	Barik et al., 2019 [21]
qLD12.1	Leaf drying	Barik et al., 2019 [21]
qHI9.1	Harvest index	Barik et al., 2019 [21]
qSF9.1	Spikelet fertility	Barik et al., 2019 [21]
qRWC9.1	Relative water content	Barik et al., 2019 [21]

Table 1: QTLs associated with drought tolerance

Out of these, qDTY1.1 has been extensively used for selection as a yield trait under drought stress of rice plants [13]. qDTY1.1 is reported to have consistent effect on grain yield under stress in reproductive-stage and non- stress conditions [5]. Numerous QTLs associated to many secondary traits such as root architecture, leaf water status, panicle water potential, osmotic adjustment, and relative water content, etc., were also identified [6]. But no major genes that regulate these traits were discovered; mainly due to low mapping resolution and weak phenotypic expression [6]. However, over 5000 genes upregulated and 6000 downregulated are differentially expressed during drought stress in rice [23].

3. Breeding approach for drought tolerance:

Screening, genetical study and selection led to establishment of some highly drought tolerant varieties. IRRI developed and released several such rice varieties like Sahabhagi dhan, and DRR dhan 42, 43 and 44 in India. Field trials of these varieties showed an average yield advantage of 1.0–1.5 tons per hectare over drought-susceptible ones under drought conditions [28]. Mega varieties like Swarna, IR64, MTU1010, Samba Mahsuri are susceptible to drought [24]. Introgression of drought tolerant traits in them can be highly impactful. Genotypes having QTLs associated to drought resistance can be exploited by using them as donor parents in conventional breeding programmes through marker-assisted selection for development of drought tolerant high yielding rice variety [2, 6]. After hybridization the population can be screened with SSR markers linked with various QTLs for quick and precise profiling of the rice lines. Such marker-assisted breeding approaches were mostly carried out in the last decade at International Rice Research Institute [25, 26]. The main disadvantage of crossing between two cultivars is linkage drag. To minimize the donor genome content marker-assisted backcrossing approach can be used (Fig:1). Here we can control the target gene (foreground selection), the genetic background (background selection) and the linkage drag (recombinant selection) using markers. Through marker assisted backcrossing, several QTLs like qDTY9.1, qDTY2.2, qDTY10.1 and qDTY4.1 were incorporated into IR64, one of leading rice cultivars. Likewise, other 5 QTLs; qDTY1.1, qDTY2.1, qDTY2.2, qDTY3.1 and qDTY3.2 were introgressed in Samba Mahsuri, a long duration drought susceptible mega variety [5]. From a cross between drought tolerant indica variety Nagina 22 and a popular variety Swarna a recombinant line IR86918- B-305 was developed which was further used as a donor parent in other breeding programs. Drought-tolerant elite

Malaysian rice cultivar MR219 was developed by pyramiding three QTLs, qDTY2.2, qDTY3.1 and qDTY12.1 [27]. Dixit et al (2017) developed a rice variety TDK1 for high yield under drought by incorporating of three QTLs (qDTY3.1, qDTY6.1 and qDTY6.2). Although remarkable progresses have been achieved through marker-assisted breeding, maintenance of yield in rice under drought conditions is very complex as yield is a dependent trait controlled by the cumulative effects of several independent traits. Transgenic approaches can be followed to improve growth and yield characteristics. Several genes/QTLs have been tested for imparting drought tolerance in rice under controlled conditions, but it is necessary for understanding the responses of these genes under drought in field conditions.

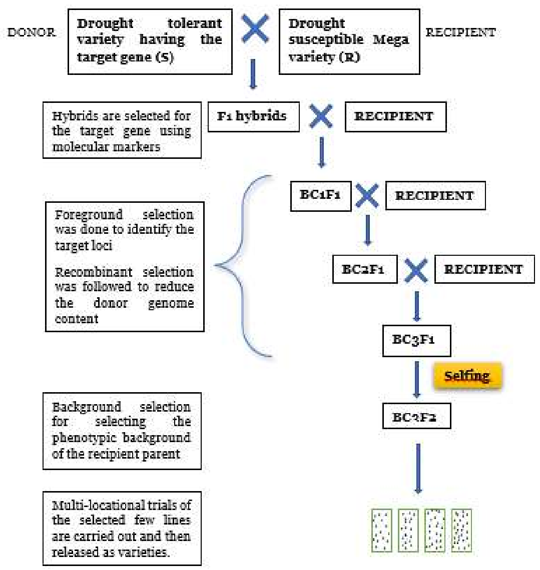

Fig 1: Schematic diagram of MAB (Marker-assisted backcrossing)

4. Plant response in drought:

Plant response to stress conditions occurs through several changes at multiple levels (molecular, biochemical, physiological, developmental, and morphological levels) [29]. All these changes are brought about by altering the expression of stress-inducible genes [30]. In general, genes associated with drought resistance are numerous and interact with the environment in different ways and thus plants take up several different mechanisms to survive in water stress conditions. Mainly three mechanisms to survive drought conditions have been unravelled, i.e., Drought resistance, avoidance, and escape. Several factors like plant genotypes, the age of the plant, its developmental stage, and the severity of drought are involved in the expression of these mechanisms [29, 31, 32].

Drought resistance/tolerance: Drought resistance is the ability of a crop to tolerate the water deficit condition and produce its economic product with minimum loss as compared to the yield in a non-stress or stress-free situation [29, 33]. So simply they acclimatize with the situation and interact with the environment to bring about some changes in them to survive. Rice crop responds to drought condition by stomatal closure, leaf rolling, enhanced root growth, enhanced ABA production, etc., to minimize water deficit [31, 35]. Drought tolerance has some other definitions too. A plant's ability to maintain its leaf water potential under water stress is also a way of resisting drought. At low tissue water potential, drought tolerance enables the plants to sustain water deficits to maintain their metabolic function even when the tissue water potential is significantly lowered [34, 36].

Drought avoidance: Drought avoidance follows the mechanism of reducing water loss from plants in water stress conditions. This is achieved through stomatal control of transpiration and higher uptake of soil moisture from deeper soil layers by growing an extensive root system [33, 38]. Root length, density, depth, and total biomass are the main traits that contribute to the final crop yield in drought avoidance mechanisms [33, 37]. Rice varieties that avoid drought usually have deep, coarse roots with a high ability of branching and penetration, higher root-to-shoot ratio, elasticity in leaf rolling, and high cuticular resistance [29, 39]. So, basically, it is the ability of plants to maintain relatively higher water potential despite of facing a shortage in soil moisture. Such varieties, therefore, minimize yield losses and avoid drought.

Drought escape: Drought escape is the ability of a plant to shorten its life cycle i.e. it tends to complete its life cycle before there is any serious hindrance of soil water deficit [29, 33]. Drought stress causes maximum damage in the flowering stage. Rice varieties following this mechanism have developmental plasticity and can prepone their flowering stage to escape from drought conditions. These lines are also able to remobilize pre-anthesis assimilates to the grain [41]. This occurs where terminal drought is prevalent. The phenological development of the plants matches perfectly with the period of availability of soil water. [33, 40]. In drought-prone upland areas of eastern India and Bangladesh, drought escape is an important mechanism that allows rice varieties to produce crop yield despite limitations in water availability [29, 42].

All these mechanisms interact with the environment and cause different molecular, morphological, physiological, and biochemical changes in rice plants (Fig 2). In molecular responses, drought stress may induce the expression of some genes that encode defense-related proteins, protein kinases, and transcription factors. Transcription factors (TFs) can regulate a series of related genes expression which are critical components of the abiotic stress signal transduction pathway. Some such examples are APETALA type 2/ethylene responsive factors (AP2/ERF), domain binding transcription factors (WRKY), ABA-responsive element binding protein 1 (AREB1), dehydration responsive binding protein (DREB) genes, etc. [4, 43, 44].

Similarly, morphological changes are also observed In stressful situations. Plants react by slowing down their growth [45, 46]. It reduces the rice seed germination percentage, slows the growth of seedlings [47, 48], and lowers the number of tillers [48, 49] and plant height [48, 49, 50]. Overall plant biomass is decreased. [51] Leaf area decreases to reduce transpiration rate. Leaf rolling is positively correlated with drought tolerance [66, 67].

An important physiological response of plants to tolerate drought is to maintain turgor pressure by reducing plant osmotic potential. [52]. Various physiological aspects of rice get affected by water stress conditions. Net photosynthesis [53], and transpiration rate [54] is reduced. It also negatively affects stomatal conductance [55, 56] water use efficiency [57] relative water content [57, 58], and membrane stability index [59].

In biochemical changes, the activity of proline is very important. An increase in the proline content has been observed in drought stress. Proline acts as an osmolyte and its accumulation contributes to better performance under water stress [2, 49, 52, 59, 60, 61]. Another common effect of drought stress is the imbalance between ROS production and its quenching in rice which reacts with proteins, lipids, and deoxyribonucleic acid causing oxidative damage in the plant [62]. ROS includes superoxide radicals, singlet oxygen, hydroxyl free radicals, and hydrogen peroxide. It causes peroxidation of lipids, denaturation of proteins, and mutation of DNA and adversely affects the plant life cycle [4, 62]. Plant cells are protected against these detrimental effects of ROS by a complex antioxidant system that includes both enzymatic and non-enzymatic antioxidants. The enzymatic antioxidants include superoxide dismutase (SOD), catalase (CAT), guaiacol peroxidise (GPX), enzymes of the ascorbate-glutathione cycle, ascorbate peroxidase (APX), etc. whereas Ascorbate (AsA) and glutathione (GSH) act as non-enzymatic antioxidants within the cell [4]. With the increase in drought stress, the activities of Ascorbate, glutathione, ascorbate peroxidase [63], superoxide dismutase [64], phenylalanine ammonia-lyase, and catalase [65] consistently increase in rice. The superactive antioxidant defense enzymes represent the protective role against the oxidative injury promoted by drought conditions in rice [4].

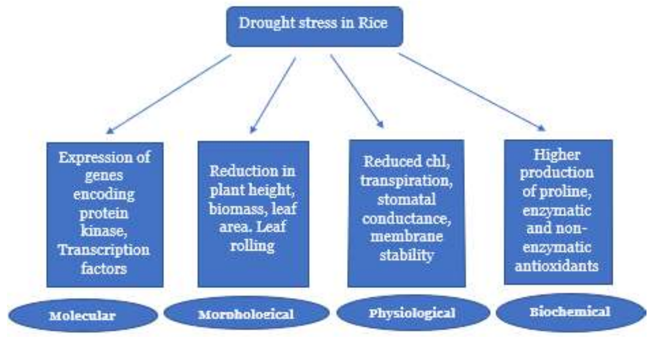

Fig 2: Different types of stress response at molecular, morphological, physiological, and biochemical levels of Rice.

4. Conclusion

Drought is recognized as one of the most disastrous stress in rice cultivation. It leads to total crop failure. Being a very complex and unpredictable trait, it is tough to apprehend the drought-tolerant trait in high-yielding mega varieties. Though some successful crosses were made their yield stability varied with varying degrees of drought stress. So, to facilitate the development of drought-tolerant varieties screening of germplasms at the field level should be done with more precision. Morphological traits like coarse and deeper roots, initiation of leaf rolling, early flowering, etc. can be considered for selection under stress conditions. Some physiological characteristics like reduction of transpiration, maintenance of membrane stability and plant water potential, etc. are crucial for selection. Higher proline accumulation and production of peroxidase, superoxide dismutase, and catalase are positively correlated with drought tolerance. The development of tolerant varieties can also be accelerated by using SSR markers associated with drought-tolerant QTLs. Keeping all these aspects under consideration, we should focus on the yield attributes of a plant under drought stress as it is the most crucial factor from a farmer's point of view. Despite ample research, there is a need for a more detailed study and characterization of the response and effects on plants due to water stress. Then only we can move forward towards the success of ensuring global food security.

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