*https://doi.org/10.33472/AFJBS.6.11.2024.1223-1240*

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

# EMPHASIS ON RICE CROP DROUGHT TOLERANCE: MODERN MECHANISMS AND STRATEGIES

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**Article Info**

Volume 6, Issue 11, July 2024

Received: 23 May 2024

Accepted: 20 June 2024

Published: 09 July 2024

doi: 10.33472/AFJBS.6.11.2024.1223-1240

## ABSTRACT:

Drought stress severely limits rice production, causing significant monetary losses. Global climate change is becoming a more significant problem, and enhancing agricultural yield in drought-prone rainfed areas is crucial for meeting global food demand. Rice varieties with drought tolerance are needed to achieve production objectives in rain-fed areas. Genetic improvement for drought-tolerant rice varieties should be a high priority in the future. However, breeding for drought-tolerant rice varieties is complex, and multigenic regulation of drought-tolerant features could be a significant roadblock. Recently, efforts to improve crops have focused on creating drought-tolerant rice varieties. To make rice more resistant to drought in a range of agro-climatic conditions, breeding methods have changed from traditional to molecular. Breeding for drought tolerance is a thought-provoking task due to its complex nature and multigenic control of drought-tolerant traits. Progress has been made in understanding the mechanisms involved in adaptation and tolerance to drought stress in rice, with recent advancements in physiological, biochemical, and molecular adaptation. Future crop improvement programs will focus on molecular genetics and breeding approaches for drought tolerance in rice.

**Keywords:** Adaptation, Climate Change, Drought Stress, Drought Tolerance, And Water Deficit Tolerance.

## 1. INTRODUCTION

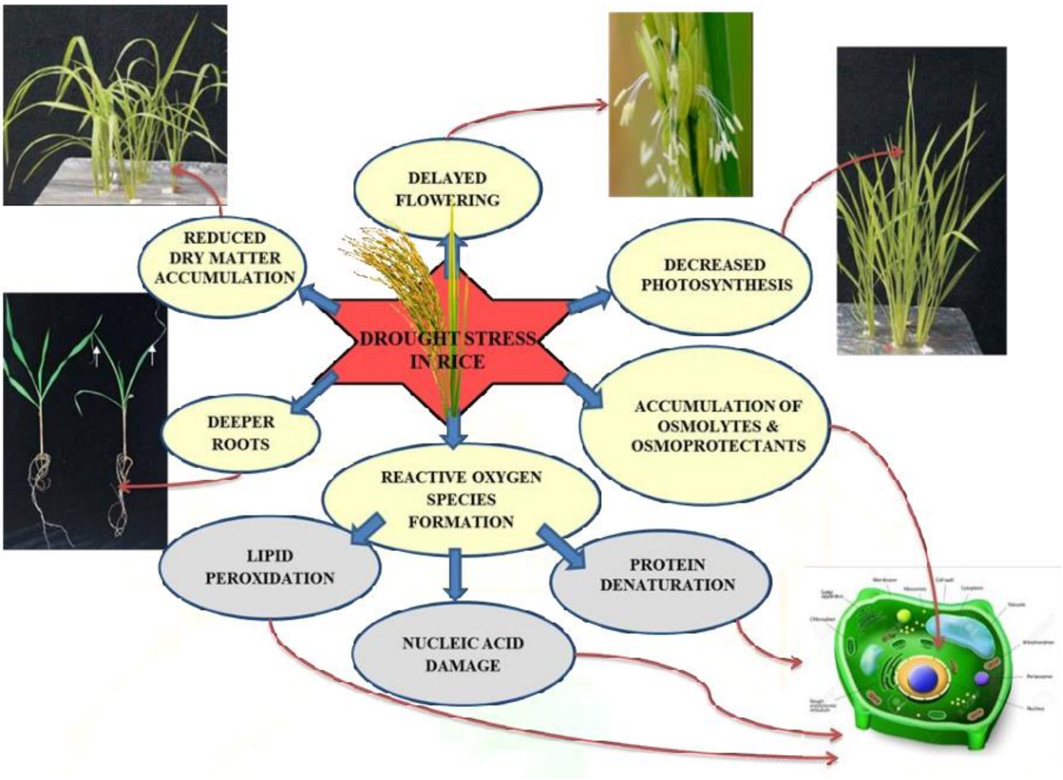
Rice is grown in a variety of ecosystems and is exposed to various environmental stresses such as drought, salinity, submergence, cold, and so on. Drought is an important yield-limiting determinant. Rising demand and declining water availability are threatening India's food security and prosperity. Out of 42.63 million ha of area under rice in India, drought is one of the major abiotic constraints in around 8.0 million ha of rainfed upland and rainfed lowland situations. Eighteen percent of India's total rice area and 20 percent of Asia's are drought-prone. The irregularities in the Southwest monsoon do result in moderate to severe drought in rainfed rice-growing areas, especially in eastern India. A number of morphological, physiological, and phenological traits have been reported to improve rice-challenged areas' performance.

Over one-third of the world's population consumes rice as a staple meal, with Asia being the top producer and consumer. Rice's small root system, thin cuticular wax, and quick stomata closure make it vulnerable to drought (FAO report, 2020–2021). To achieve self-sufficiency in rice production by 2050, high-yielding varieties with tolerance and resistance to biotic and abiotic stressors under adverse climatic conditions are needed [108, 81]. Drought is one of the most destructive abiotic elements, resulting in complete yield losses depending on the plant's stage of growth [29]. The two main factors limiting rice production are the severity of dry spells and the lack of high-yielding genotypes that can thrive in dry-season conditions. Reduced water supplies from groundwater exhaustion frequently have an impact on rice development, which can result in male sterility and early organism termination. Extreme dry spell pressure can harm plant growth at all stages, resulting in low regenerative success for most plant species. Understanding how plants respond to pressure is crucial for planning organisms that are impervious to such pressure. Climate, genotype, and the interaction between genotype and climate all have an impact on a plant's development and growth. The biochemical activities affected by ecological impacts are crucial for improvement. Two main types of dry season conditions are terminal and discontinuous, with terminal spells causing extreme pressure and death and discontinuous spells allowing plant development to endure periods of lack of water. Irregular dry spell conditions are usually not lethal. The focus on the dry season has increased. However, studying dry spell reactions is difficult due to the complexity of the dry season-tolerant quality. The Global Rice Exploration Foundation (IRRI) has analyzed nearly 1000 quality bank varieties from 47 countries for dry season resilience, finding 65 more aus or indica varieties that can endure dry spells. For modern yield varieties, the most promising sources of dry season traits are those that exhibit exceptional drought resistance.

### Responses of morphology to drought stress

The capacity of a plant to generate its maximum commercial amount when faced with water scarcity is known as drought resistance [46]. It is a multifaceted characteristic including physiological, biochemical, and anatomical reactions. Drought avoidance is the capacity of a plant to retain high tissue water potential in the face of soil moisture deficiencies, while drought escape is the ability of a plant to finish its life cycle before soil water deficits arise. The capacity of a rice plant to endure low tissue water content is known as drought tolerance. Depending on the extent, interlude, and plant stage, drought damage affects crop growth metrics and production. According to [28], illustrates the harmful effects of drought stress on the morphological, physiological, biochemical, and molecular processes of the plant presented in figure 1.

**Figure 1:** A schematic diagram showing morphological and physiological effect of drought in rice



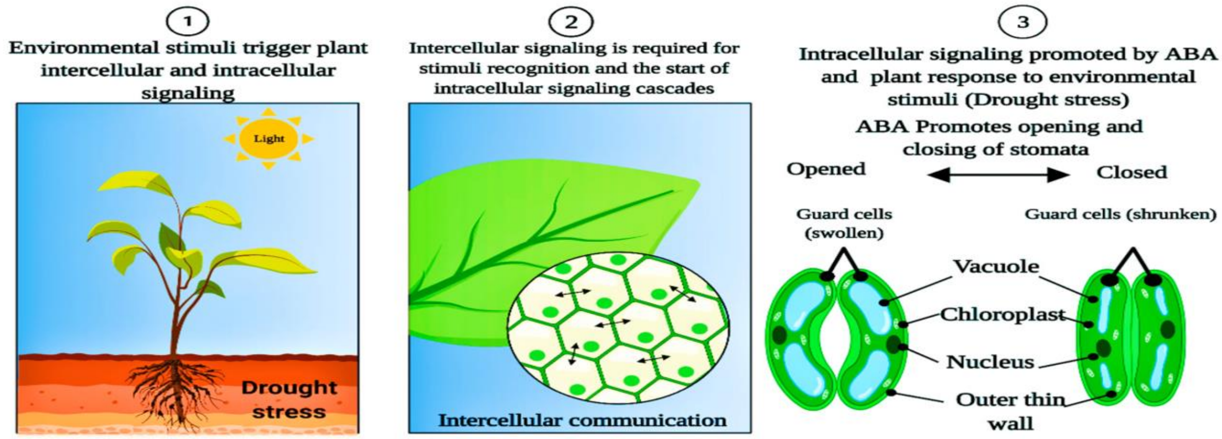
### 1.1. The impact of drought stress on seed germination and seedling growth

Studies show that water stress modifies the early morphology of rice, resulting in decreased growth and aborted germination. Drought stress significantly affects rice germination and seedling development because of water constraint. During germination and the early stages of seedling development, rice is very vulnerable to dry conditions and needs the right temperature and soil moisture content. Drought impairs the absorption of water, weakens seedlings, and upsets the water balance, which damages metabolic processes, hinders membrane transport, lowers respiration, and produces less ATP [23]. All of these factors contribute to poor seed germination. According to a number of studies, plants under water stress had lower biomass, leaf area, and height [48,37 ]

### 1.2. Characteristics of leaves under drought stress

Due to the leaf's reduced water potential, drought stress inhibits leaf development [58,40] . Crops that experience this have reduced leaf area and impaired cell growth [21] the morphology and ultra structure of the leaf have changed, according to [53]. These changes include the leaf size shrinking, fewer stomata, a thick cell wall, cutinization, and inadequate growth of the conducting system. Important traits under drought stress include leaf rolling and early senescence [2]. To find drought-tolerant cultivars, researchers have used a number of leaf characteristics, including greater flag leaf area, leaf area index, leaf relative water content, and leaf pigment content presented in figure 2 [12,37,21].

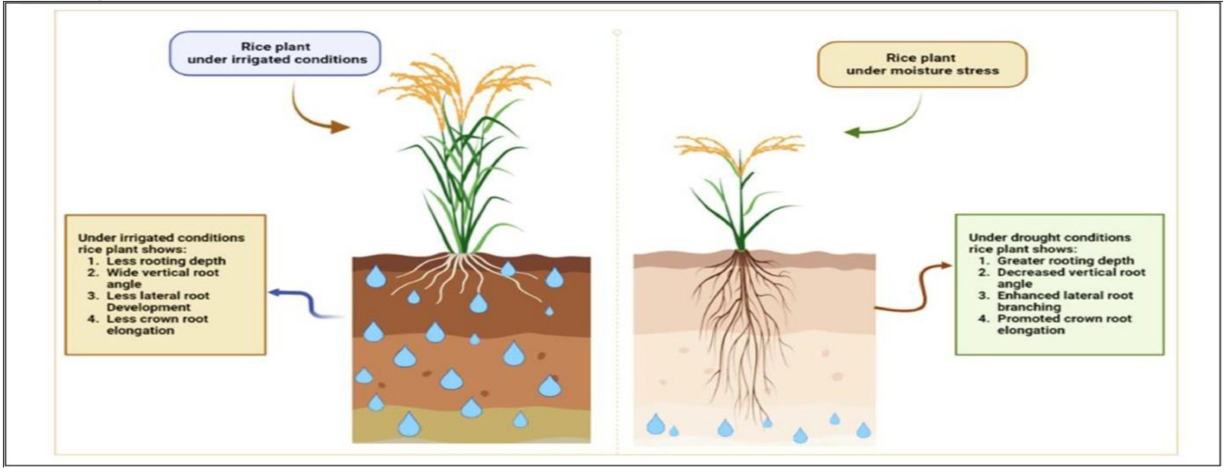
**Figure 2.** Abscisic acid (ABA) is vital for plant development and stress response. In response to biotic and abiotic stimuli, ABA transfer to guard cells triggers stomatal closure in leaves.



## 2. 3. The effects of drought stress on root traits are significant

Plant roots have a critical role in increasing yield in drought-stressed environments. Crop function is determined by the composition and development of the rice root system. In order to anticipate rice output, we can forecast root mass and length. Different cultivars have different root development characteristics when subjected to water stress; cultivars with deep and extensive root systems exhibit more flexibility. Drought tolerance is mostly dependent on rice genotypes with large root systems, coarse roots, and high root-shoot ratios. Under drought stress, the morpho-physiological traits of rice roots have a major impact on shoot development and total grain output [36,26] .

**Figure 3 :** Rice root system plasticity under irrigated and water-stressed conditions.



## 2.4 Effect of drought on physiological responses

Drought stress has a negative impact on plant physiological processes, necessitating optimization of parameters and processes before breeding programs to increase yield in adverse drought conditions. According to studies conducted by [7, 3, 15] the impact of drought stress on plant physiological processes is significant. When rice doesn't have enough water, its physiological traits suffer. Some of these effects include a decrease in the net photosynthetic rate, transpiration rate, stomatal conductance, water use efficiency, internal CO2 concentration, photosystem II activity, relative water content, and membrane stability. According to studies conducted by [12, 7, 36,58] .

### 2.5. The impact of drought on the process of photosynthesis in rice leaves

Water deficits and drought stress influence photosynthesis, a crucial metabolic process in crop growth and production. Water stress changes the rate of photosynthesis and the way plants exchange gases, which causes stomata to close, carbon dioxide to flow less, and reactive oxygen species to form more [12,36]. Several factors are involved.

### 2.6. Effect of drought stress on water relations and membrane functions

Water use efficiency (WUE) may enhance crop performance during droughts and is a critical component in evaluating plant yield potential under water stress circumstances. A crucial component of plant water relations is relative water capacity (RWC), which expresses differences in turgor potential and water potential [15]. In many plant cultivars, water stress has a detrimental impact on transpiration, turgor pressure, and RWC [5]. Four-week-old rice seedlings with higher proline content showed a consistent improvement in RWC against drought [45]. Plants are known to be able to endure a constant membrane index. This is due to the fact that when a plant experiences water stress; the lipid structure is harmed and altered, rendering the membrane more permeable. To comprehend their relationship with rice output under drought stress, researchers have used the characteristics of cell membrane stability (CMS) and membrane stability index (MSI) [53].

### 2.7. The effects of drought stress on biochemical characteristics are significant.

Plants cope with drought stress by accumulating organic and inorganic solutes that lower their osmotic potential. They accumulate osmoprotectants like proline, glycinebetaine, and soluble sugar, which provide osmotic adjustments [28, 53]. Protein content and antioxidant activity improve drought tolerance, while tissue- and time-specific expression of drought-response traits improves drought response without affecting yield [15].

### 2.8. Under drought stress, osmolyte accumulation

Osmoregulation is an important process in plants. When turgor levels drop, osmoprotectants like proline, soluble sugar, phenolic contents, and total free amino acids build up. Proline, a proteinogenic five-carbon amino acid, is essential for drought tolerance and maintains leaf turgor and stomatal conductance. Its accumulation increases under water deficits, making it a biochemical marker for drought screening in plants. Rye grasses are the first to report proline content under water deficit stress. The sources for this information are [41] and [36].

Carbohydrates, a structural unit providing energy for plant biomass, play a crucial role in stress tolerance, with disaccharides, oligosaccharides, and fructans being key type [25] . Soluble sugars are crucial for balancing physiological processes like photosynthesis and mitochondrial respiration [14]. Plants use sugar-based strategies to adapt to environmental stresses, with mannitol, sorbitol, and trehalose playing essential roles in growth and metabolic function [27]. Drought causes the accumulation of soluble sugars, which acts as osmoprotectants and protects plants to some extent. These findings have been reported by [28,53].

### 2.9. The production of reactive oxygen species occurs under drought stress

Although ROS are a normal result of aerobic metabolism, biotic and abiotic stressors may cause excessive synthesis of these molecules, which can harm cells and kill plants[14]. In different cytosol segments, ROS are produced by respiration and photosynthesis. Drought may result in an imbalance between quenching and ROS generation, which may harm plants oxidatively and disrupt their life cycle. Electron leakage to O2 is detrimental to photosynthesis and causes the Mehler reaction, which produces ROS. In addition, superoxide, hydrogen peroxide, and hydroxyl radicals are produced in excess during a drought, which damages cell components and causes cellular death [14]. To improve rice's resistance to drought, Fig. 2 suggests either lowering ROS overproduction or increasing antioxidant activity in rice organs.

## 2.10 Role of antioxidants under drought

Enzymatic and non-enzymatic antioxidants make up the defense mechanism against free radicals in plants. Guaiacol peroxidase (GPX), ascorbate peroxidase (APX), glutathione reductase (GR), monodehydroascorbate reductase (MDHAR), and dehydroascorbate reductase (DHAR) are a few enzymes that function as antioxidants. Antioxidants that are not enzymatic include glutathione (GSH) and ascorbate (AsA). Rice's resistance to drought stress can be increased by promoting the expression of these antioxidants, which may work as a defense against oxidative stress and strengthen drought tolerance mechanisms [32,36,35].

## 2.11 Molecular mechanism of drought tolerance

Membrane sensors detect environmental drought stimuli and transmit them through signal transduction pathways, resulting in drought-responsive qualities with appropriate gene functions and tolerance. Drought is a complex phenomenon, making hybridization and selection strategies difficult to understand. However, DNA markers in molecular studies can provide precise results and aid in screening drought-tolerant germplasm for crop improvement. Many studies have focused on establishing qualitative trait loci (QTL) related to various traits. Researchers use DNA studies based on marker-based phenotyping to identify genes involved in drought resilience in rice. Molecular breeding can lead to improved crop varieties, increased yields, and safe, high-agronomic harvests. According to studies conducted by [7, 38, 57, 42], molecular breeding can lead to improved crop varieties, increased yields, and safe, high-agronomic harvests.

## 2.12 Quantitative trait loci (QTL) in rice are linked to drought tolerance.

Plant genomes contain genes known as quantitative trait loci (QTL), which exhibit precise quantitative traits and are associated with various agronomic traits during drought conditions. Earlier molecular genetics studies identified numerous QTLs linked to physiological and biochemical traits, but they failed to identify any gene that regulates these traits due to low mapping resolution and weak phenotypic effects. Researchers have extensively used the identification of these QTLs to select tolerant rice genotypes in stress screening programs for plants [1, 111, 16, 6]. Other important QTLs identified in rice for drought tolerance are predominantly non-elite genotypes. Some of the most important QTLs identified in different rice lines include qDTY1.1, qDTY2.1, qDTY2.2, qDTHI2.3, qDTY3.1, qDTY6.1, qDTR8, qDLR8.1, qDTY9.1A, and qDTY12.1. We also report various SSR markers linked to these QTLs for identification purposes. It will be easier to quickly and accurately profile rice lines if we use drought-tolerant QTL-linked SSR markers to test new rice genotypes for their ability to handle drought. SSR markers are speedy, basic, stable, and exceptionally polymorphic in nature. Researchers have conducted genetic studies on drought in rice using molecular markers that exhibit traits like root characters, osmotic adjustment, cell membrane stability, relative water content, leaf rolling, stomatal conductance, and grain yield [44,8,54]. In rice, they have reported five QTLs, such as qLR9.1, qLD9.1, qHI9.1, qSF9.1, and qRWC9.1, that control leaf rolling, leaf drying, harvest index, spikelet fertility, and relative water content, respectively, under reproductive stage drought stress.

### 2.13. Genes and transgenic approaches for drought tolerance in rice are being explored.

Following drought stress exposure, rice undergoes differential expression of various genes, with approximately 5000 genes unregulated and 6,000 down regulated.[4] as well as [22] have conducted studies on this topic. The study identifies three major categories of genes and their functions in relation to rice drought tolerance: related membrane transport, related signaling, and transcriptional control. [53,26 ] are the sources of this information. The expression of genes and transcription factors in rice is crucial for controlling biochemical, physiological, and molecular mechanisms under drought stress. Most genes are ABA-independent or ABA-independent, controlling drought tolerance mechanisms in rice. Through ABA signaling, OsJAZ1 attenuates drought tolerance, orchestrating plant responses to growth and development under drought stress. Other genes, such as DRO1 and OsPYL/RCAR5, induce root elongation, deeper rooting, leaf water content, delayed leaf rolling, higher root and shoot mass, and stomatal regulation in rice under water deficit conditions. The studies conducted by [26,43] support these findings. Overexpression of OsDREB2B, CYP735A, and OsDREB1F also increased root morphological adaptations in rice under drought stress [26][20] reported that the DREB2-like gene OsDRAP1 confers drought tolerance in rice. Transgenic approaches achieve increased grain yield in rice under drought by introducing genes such as OsNAC5[19] OsLEA3-1 [56], OsbZIP71 [31] and OsWRKY47.

Drought has become a constraint for rice cultivation, but no effective measures have been successful in developing drought-tolerant rice varieties. Farmers often choose high-yielding cultivars with better grain quality but are susceptible to drought, or use traditional drought-tolerant varieties with poor yield. Drought breeding programs often use high-yielding varieties like Swarna, Samba-mahsuri, and IR36, yet frequent drought spells result in significant losses in rice production. Therefore, we need to focus more on improving special rice varieties that can produce high yields under drought and adapt to various adverse climatic conditions.

## 3. THE STUDY FOCUSES ON THE MECHANISMS OF DROUGHT STRESS AND THEIR RESPONSES IN RICE.

Stress is defined as the alteration of physiological conditions caused by elements that threaten a plant's stability. Drought, a climatic characteristic, is often caused by low or no precipitation and constant water loss through evaporation and transpiration. "Drought tolerance" refers to a plant's ability to produce the highest economic yield when water is scarce. Genetic variables influence this trait at various stages. "Drought escape" enables a plant to complete its life cycle before serious soil water deficits develop, whereas "drought avoidance" maintains high tissue water potential despite soil moisture shortages, as shown in Figure 4 [13].

Figure-4

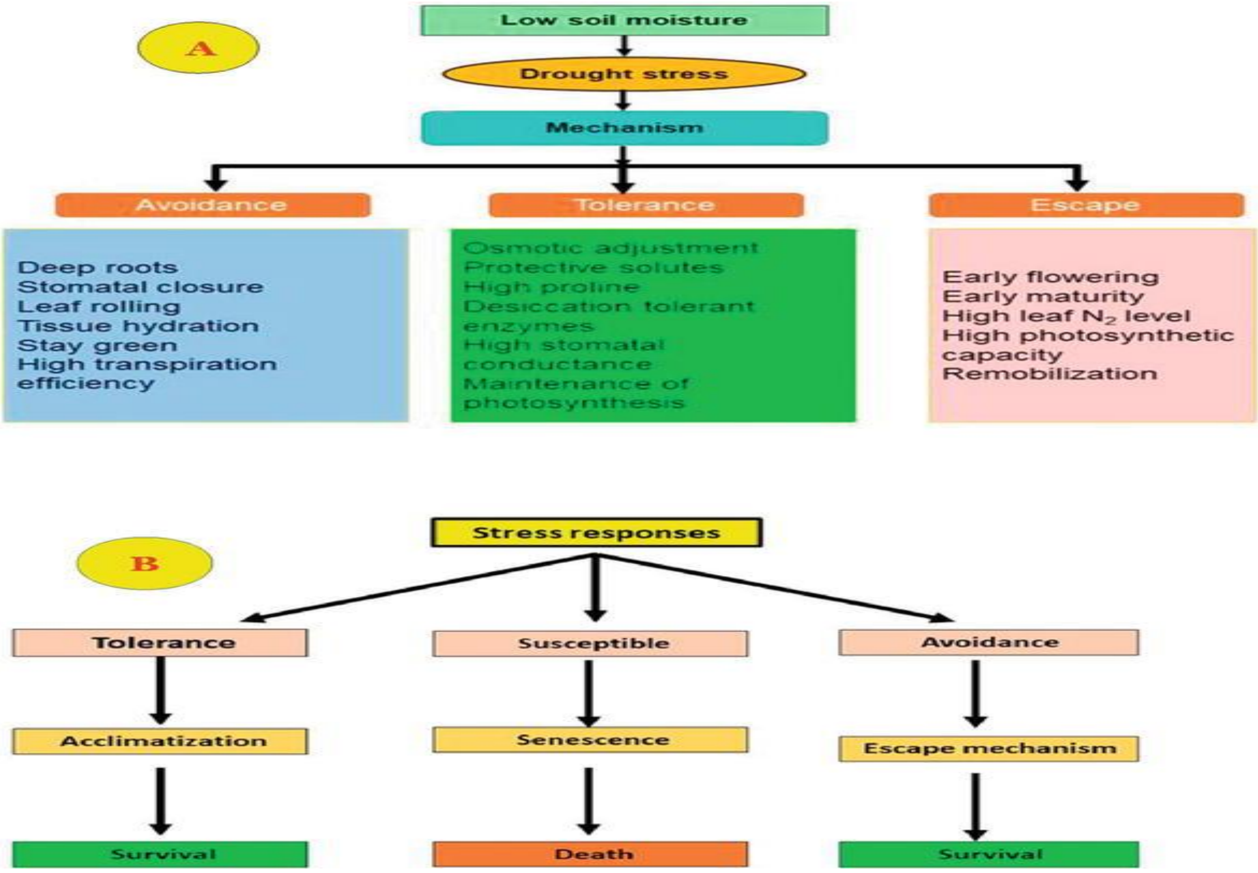
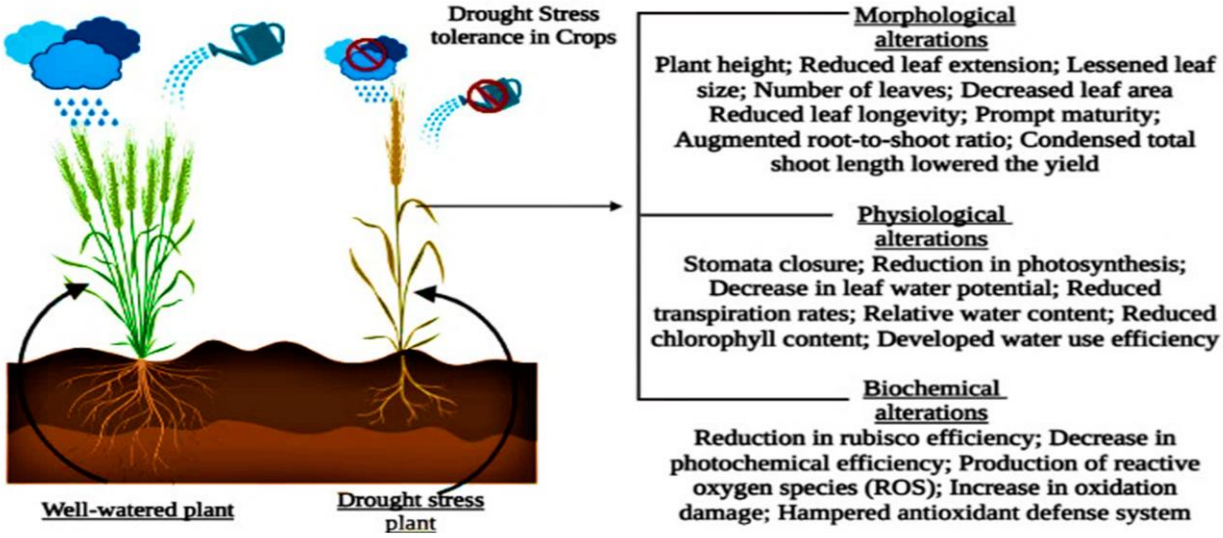


**Figure 4.**Mechanisms of drought stress and their responses to drought stress in rice. (A) Different responses and mechanism of the rice plants under drought stress; (B) Plant response mechanisms to drought stress.

### 3.1. Plant morphological characteristics react to drought stress in rice.

Early-stage morphological alterations in rice caused by water stress have an impact on seed germination and production. Poor seed germination is the consequence of drought stress, which also affects membrane transport, ATP production, respiration, and water balance. Additionally, it results in reductions in biomass, leaf area, and plant height. Reduced leaf area and poor cell development are the results of low water potential, which also hinders leaf growth. Conditions that are stressed by drought also have an impact on the leaf's anatomy and ultrastructure. For maximum yield, it is thus essential to create a crop stand as soon as possible [53]. Reduced leaf size, fewer stomata, thicker cell walls, cutinization of the leaf surface, and inadequate system development are some of these changes [46]. Plants under drought stress display characteristics including early senescence and leaf rolling. To find drought-tolerant types, we take into account variables such as leaf area, leaf area index, relative water content, and leaf pigment content. Crop function in rice is determined by the structure and growth of its root systems; these features are critical for improving yield. Rice yield may be predicted using root mass and length when the plant is under water stress. Rice varieties that have large, deep roots are more resilient to drought. The morph physiological characteristics of rice roots greatly influence the development of shoots and the overall yield of grains are presented in figure 5. Increased root area, longer root lengths, waxy or thick leaf coats, fewer epithelial cells, postponed leaf senescence, and more green leaf area are examples of adaptations [16, 47, and 35]

**Figure 5.** Drought stress impacts plants’ morphological, physiological, and biochemical processes.



### 3.2 Plant physiological traits respond to drought stress in rice.

Drought or shortage-induced water stress affects photosynthesis, a vital metabolic process in crop growth and yield. When water is scarce, stomata shut down, reducing carbon dioxide and driving reactive oxygen species reactions. Stomatal closure, turgor pressure loss, reduced leaf gas exchange, and decreased CO2 uptake influence this decline. Relative water content (RWC) is a crucial measure of plant water status, capturing changes in water potential and turgor potential (36,39). Drought stress leads to a decrease in plant water content, reduced cell length and growth, stomatal closure, decreased gas exchange, and disruption of enzyme-catalyzed activities. It also disrupts photosynthesis and metabolism, leading to plant death. Drought stress inhibits cell growth, impacting various biochemical and physiological processes. Adapted cells have a higher chlorophyll content, a lower osmotic potential, and a lower harvest index. Physiological acclimation, such as higher stomatal density and conductance, lower transpiration rates, improved production, accumulation, assimilation, and yield partitioning, also contributes to the effects of drought stress. [52,49].

### 3.3 Rice plant biochemical characteristics react to drought stress

Plants store both organic and inorganic solutes, reduce their osmotic potential, and use osmoprotectants such soluble sucrose, proline, and glycinebetaine to cope with drought stress. Improved drought resistance is influenced by factors like as protein content, antioxidant activity, and tissue- and time-specific expression of drought-responsive traits including ethylene phytohormone pathways, abscisic acid, and brassinosteroids. [28, 11, 15]

#### 3.3.1 Osmolyte buildup in a rice environment under stress from drought

Osmoregulation is essential to plants' ability to control their turgor, which is necessary for life maintenance. Drought resistance is mostly influenced by the build-up of osmolytes, which include proline, soluble sugar, phenolics, and total free amino acids, when water shortage occurs. Unbalances in the supply and loss of water are detected by plant cells, which then convert them into cellular stress signals that trigger drought tolerance mechanisms. Plants possess an advanced signaling system that disseminates stress signals throughout the plant via main and secondary channels [18,2]. Plants use osmotic adaptation to decrease the osmotic potential of their cytoplasm by accumulating both organic and inorganic solutes. Sucrose, glycine betaine, and proline are necessary for preserving leaf turgor and promoting stomatal conductance. Leaf turgor is maintained and drought tolerance is improved by increased proline accumulation. Under abiotic stress, carbohydrates—such as fructans, oligosaccharides, and disaccharides—are essential for stress tolerance. Together with supporting plant biomass, they also aid in physiological processes including mitochondrial respiration and photosynthesis. For plants to develop and function metabolically, mannitol, sorbitol, and trehalose must be available [27.28,53].

### 3.3.2 The role of antioxidants in drought stress

Plants are shielded from oxidative damage by an antioxidant defense mechanism. Rice is more drought-tolerant because it expresses antioxidants. On the other hand, aberrant quenching and ROS formation brought on by dryness may cause oxidative damage, which will have an adverse effect on the plant's life cycle. This is because ROS, which has a detrimental effect on photosynthesis, is produced via the Mehler reaction. Hyperbolic concentrations of superoxide, hydrogen peroxide, and hydroxyl radicals cause cellular death. Reducing ROS generation or enhancing antioxidant activity is the best way to increase rice's tolerance to drought. The mechanism of ROS generation, the detrimental consequences of oxidative stress, cell damage, and different antioxidant systems are shown in Figure 6.
Figure 6.

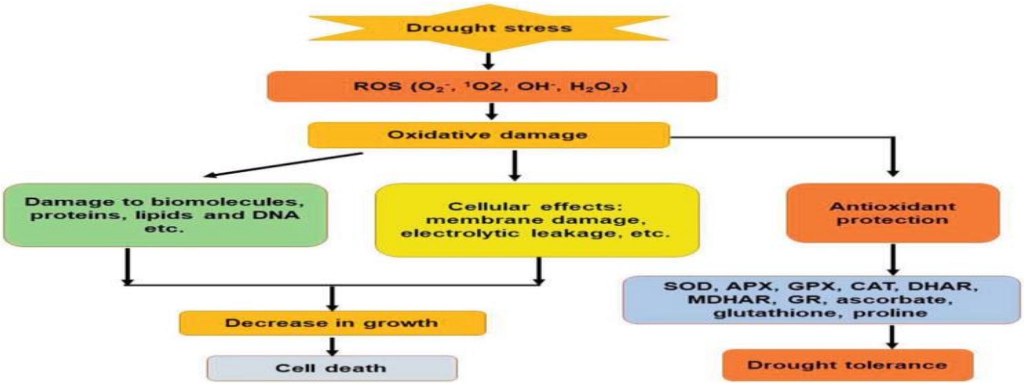


**Figure 6.** Schematic representation of reactive oxygen species (ROS) damage and antioxidant protection of rice plants under drought stress [44]. APX, ascorbate peroxidase; CAT, catalase; DHAR, Dehydroascorbate reductase; GR, glutathione reductase; GPX, guaiacol peroxidase; MDHAR, monodehydroascorbate reductase; SOD, superoxide dismutase.

ROS, which include hydroxyl free radicals, have the ability to disturb cellular homeostasis, lipid peroxidation, protein denaturation, and DNA mutations. Plants have a sophisticated antioxidant system made up of both enzymatic and non-enzymatic substances that shields them from these damaging effects. MDHAR, DHAR, SOD, CAT, GR, APX, GPX, and ascorbate-glutathione cycle enzymes are examples of enzymatic antioxidants. Rice's enzymatic and non-enzymatic antioxidant activity is enhanced by increased drought stress. Enhancing drought resistance and guarding against oxidative damage may be achieved by upregulating the expression of these antioxidant defense enzymes. [33].

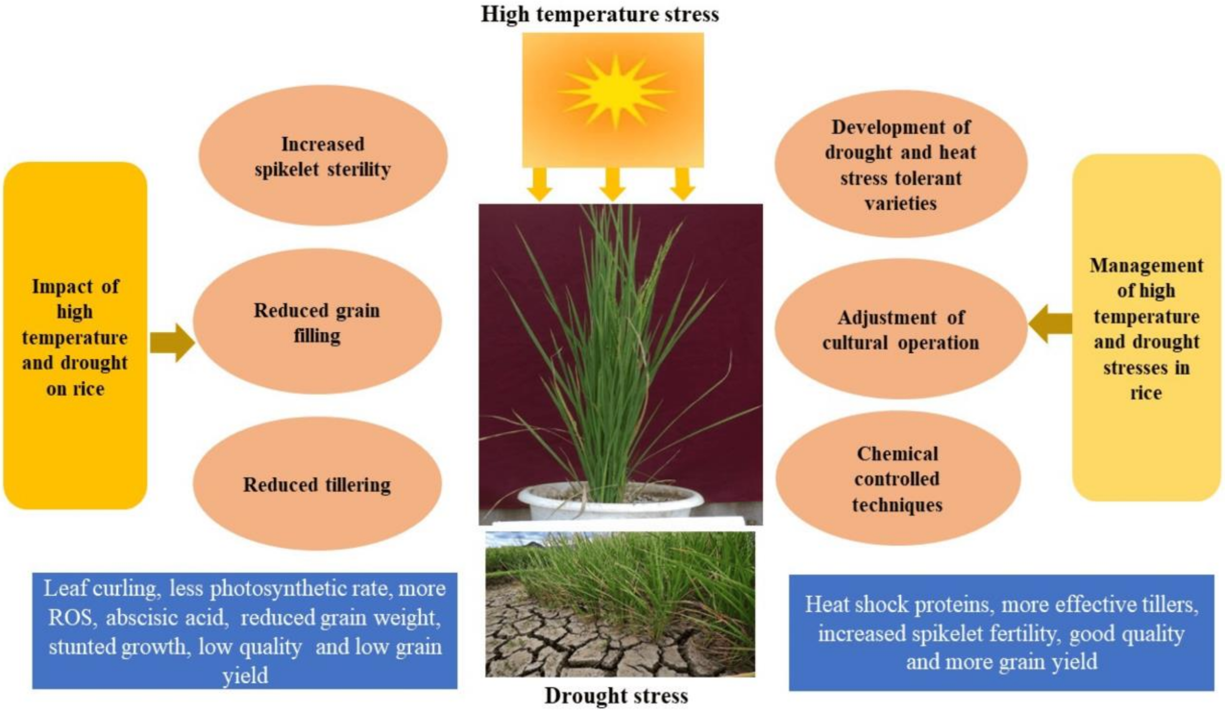
### 3.3.3 Polyamines' function in drought stress

Putrescine, spermidine, and spermine are examples of polyamines (PAs) that rice plants produce in response to drought stress. These chemicals regulate osmotic potential, membrane stability, and homeostasis. A higher PA concentration during a drought improves osmotic detoxification, reduces water loss, and boosts photosynthetic capacity. More putrescine is produced by rice, which promotes the synthesis of spermidine and spermine and shields plants from drying out. [6,33].

### 3.3.4 The function of phytohormones during a drought

Plants are able to thrive under dry circumstances with the aid of plant hormones such as gibberellins (GAs), ethylene (ET), auxins (IAA), cytokinins (CK), jasmonic acid (JA), and abscisic acid (ABA). The interaction of these hormones improves plant survival. Drought stress brought on by soil drying causes ABA concentrations to change in response to this pressure. In contrast to other hormones, ABA concentration rises in response to signs of drought stress. These intricate and dynamic changes in the endogenous levels of a hormone may be influenced by the length and intensity of the drought stress. ABA contributes to water stress signaling indirectly by inhibiting the synthesis of ET. Both ABA-dependent and ABA-independent signaling pathways are activated by drought, and research has connected enhanced drought tolerance to a rapid ABA accumulation [40, 47, and 30]. Research on the very drought-tolerant resurrection plants (Craterostigma wilmsii) has shown that ABA concentrations are most significantly impacted when drought stress occurs [34]. Significant alterations in plant development, defense systems, and drought tolerance are brought about by ABA and other hormone signaling pathways [47].

**Figure 7.** Ecophysiology responses of rice to drought and high temperature.

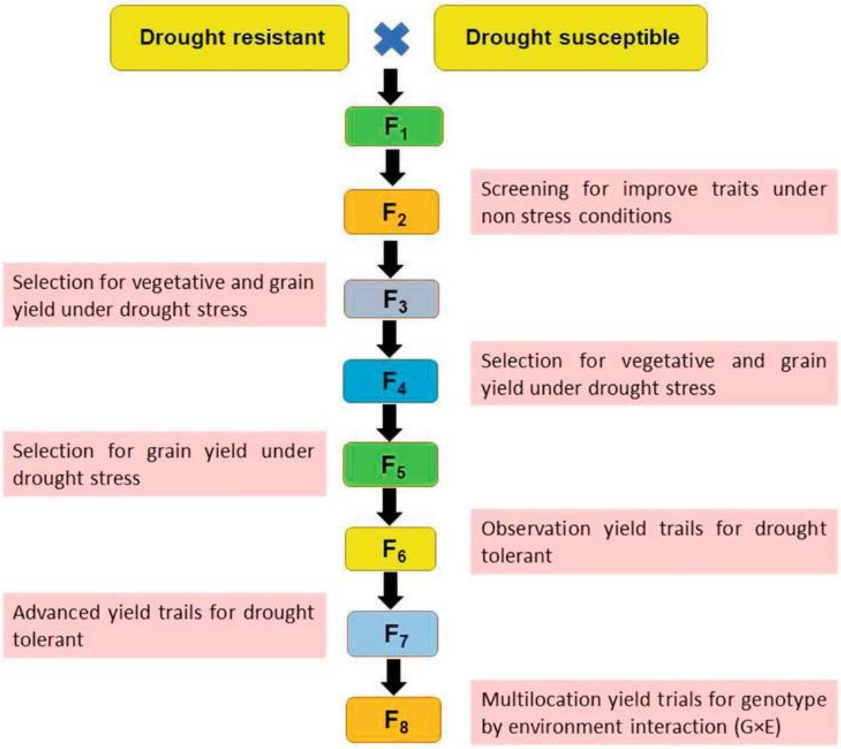


## 4. THE GOAL OF TRADITIONAL BREEDING METHODS IS TO INCREASE RICE'S RESISTANCE TO DROUGHT

Plants use phytohormones including ABA, cytokinins, and GAs to adapt to settings that are drought-prone. Drought stress signals are communicated by variations in ABA concentration brought on by drying soil. ABA contributes to water stress signaling indirectly by inhibiting the synthesis of ET. Both ABA-dependent and ABA-independent signaling pathways are activated by drought, and increased drought tolerance is correlated with a fast ABA buildup.

**4.1 Pedigree selection** Pedigree selection is a traditional breeding technique in rice development, particularly suitable for traits controlled by important genes. It allows for the combination of numerous genes that influence biotic and abiotic processes. However, it takes time and requires repeatedly evaluating lines over planting seasons. Diallel mating design is more suitable for traits influenced by multiple genes. Figure 8 presents the preference for recurrent selection over pedigree selection in self-pollinating crops, including rice.

**Figure 8.**Modified method for conventional yield trail in rice.



## 4.2 Recurrent selection

In rice varietal improvement, recurrent selection is a method that increases beneficial allele frequencies while preserving genetic diversity, offering accurate genetic gains, faster breeding cycles, and diversified breeding lines, outperforming pedigree selection [24].

## 4.3 Backcross breeding

The backcrossing technique is used in rice breeding to introduce desirable genes from donors to recipient parents, reducing the donor parent's genome and increasing recovery. This precise method creates superior breeding lines and cultivars that can withstand drought, enhancing crop yield [29, 38].

## 4.4 Induced Mutation

Plant breeders use induced mutation as a technique to create new varieties, like drought-resistant rice varieties. This method has been successful in developing rice varieties that are resistant to pests and diseases, increase grain yield, and improve grain quality. We have used induced mutations to create gene alleles not found in nature, leading to numerous success stories. For instance, researchers exposed Manawthukha rice to gamma radiation to test its drought resistance, and after six generations of evaluation and selection, they determined that two mutant lines were drought-resistant. Indonesia created a super green rice mutant and developed two improved lines, MR219-9 and MR219-4, from the common MR219 rice variety in Malaysia. The development of drought tolerance often uses techniques such as transgenic, gene expression patterns, proteomics, genome-wide association, stable isotopes, and fluorescence or thermal imaging. Genetic engineering and molecular technology have been instrumental in developing rice resilience to drought, with genetic resistance being the most effective method to lessen its effects [17, 10].

## 5. THE MOLECULAR BASIS IS RESPONSIBLE FOR IMPROVING DROUGHT TOLERANCE IN RICE.

Sensors on membranes detect environmental drought stimuli, transmitting them through signal transduction pathways to produce drought-responsive qualities with appropriate gene functions and tolerance. However, hybridization and selection techniques cannot provide precise findings for drought tolerance. In molecular studies, DNA markers can help find qualitative trait loci (QTLs) that are linked to different traits, like how roots and shoots react to water and salt, how hormones work, how photosynthesis works, and how the whole plant reacts to drought tolerance. DNA studies based on marker-based phenotyping are the main methods used to identify genes involved in rice drought resistance. To create transgenic crops with improved drought resistance, it is crucial to identify candidate genes responsible for plant tolerance under various abiotic stresses. Genetic engineering and hybridization with marker-assisted selection can introduce drought tolerance genes into the genetic background of suitable cultivars, improving crop types and yield varieties, and resulting in prolific harvests with high agronomic validity and safety [28, 37, 3].

### 5.1 QTLs associated with rice drought tolerance

The plant genome contains genes known as QTLs, which have exact quantitative characteristics and are linked to a variety of agronomic features under drought. These QTLs are used by plant stress screening systems to identify rice cultivars that can withstand drought. In order to develop cultivars that are resistant to drought, research institutions all over the globe are concentrating on mapping QTLs for rice grain production under drought stress. The bulk of rice QTLs for drought tolerance are found in non-elite genotypes; qDTY1.1 is a frequently utilized yield trait. Significant QTLs have been found in a number of rice lines, including qDTY2.1, qDTY2.2, qDTHI2.3, qDTY3.1, qDTY6.1, and qDTR8. It would be possible to quickly and precisely profile rice lines by using these markers for molecular screening of novel genotypes of rice for drought tolerance. In the reproductive stage of rice, morpho-physiological characteristics linked to drought tolerance were mapped genetically. This mapping revealed five QTLs that regulate the following features: leaf rolling, leaf drying, harvest index, spikelet fertility, and relative water content. [3].

### 5.2 Rice drought tolerance using genetic engineering and transgenic techniques

Plants synthesize a variety of protein classes that aid in the creation of dependable stress pathways, such as transcriptional factors, enzymes, and molecular chaperones. These genes have been identified by genomic approaches and included into the rice genome to study their effects on drought tolerance. Numerous transcription factors encode WRKY genes, which control a variety of biological activities in plants. Zinc finger proteins, which control stress reactions, are extensively distributed in plants. Increased proline and soluble sugar accumulation, enhanced survival chances, and improved drought tolerance are all brought about by over expressing the zinc finger protein OsZFP252. Approximately 5,000 genes in rice are up-regulated and 6,000 genes are down-regulated after exposure to drought stress.

Transgenic rice improves stomatal closure, osmoregulation, and water usage efficiency under drought stress, according to research. The WRKY genes are essential for plant growth and react to drought stress. We induced rice to produce more trehalose, better drought tolerance, and less photo oxidation by introducing a fusion TPP/TPS gene from Escherichia coli. [47, 20, 24, 9]

### 5.3 Marker-assisted selection (MAS) for rice drought tolerance

In order to find new genotypes with drought-tolerant traits and associated genes or loci, we may examine the natural genotypic variation in rice. These genotypes may be used in breeding efforts to produce rice varieties that can withstand drought. Unfortunately, the difficulty in locating appropriate donors and the environment-specific character of rice genotype breeding for drought tolerance have resulted in a poor success rate. A precise, quick, affordable, eco-friendly, and quick approach for creating excellent drought-resistant rice cultivars is provided by MAS. For the last ten years, the main location for marker-assisted breeding methods to produce rice varieties resistant to drought has been the IRRI. Several QTLs for rice drought tolerance are included into elite cultivars using marker-assisted breeding procedures. But even with the growing importance of drought, no real efforts have been made to develop rice varieties that can withstand it. High-yielding cultivars like Swarna, Samba mahsuri, and IR36 were used in drought breeding efforts, but their incapacity to endure recurrent droughts has caused large losses in rice production. Thus, more attention has to be paid to enhanced unique rice cultivars that produce well during droughts and can adapt to a variety of harsh climatic conditions [49, 28, 7, and 3, 55].

## 6. FUTURE PROSPECT

The intricate process of rice drought tolerance requires a deep comprehension of the grain's morphological, physiological, biochemical, and molecular traits. Molecularly breeding rice for drought tolerance still faces significant challenges, despite progress in marker-assisted breeding. One major obstacle to study on drought-tolerant traits is their complicated nature and multigenic control. Enhancing rice's yield and agronomic traits requires the use of transgenic techniques. It is important to comprehend how genes respond to drought in the field since certain genes for drought tolerance in rice have been researched in lab settings. Crop breeding may use advances in molecular genetics, crop physiology, and breeding techniques to enhance drought tolerance and foster genetic progress.

## 7. CONCLUSION

The development of drought tolerance in rice requires a comprehensive understanding of various morphological, biochemicals, physiological, and molecular characteristics. Despite progress made through marker-assisted breeding, there are still challenges in molecular breeding of drought tolerance in rice. The complex nature and multigenic control of drought-tolerant traits pose a major bottleneck for future research. The cumulative effect of several traits controls the multifaceted phenomenon of maintaining rice yield under drought conditions, making it crucial to identify the primary contributor to yield under drought. Researchers have found that transgenic approaches enhance the agronomic traits and yield characteristics of rice, but more research is required to comprehend how these genes respond to drought in farmers' fields. We can use advancements in crop physiology, molecular genetics, and breeding approaches to enhance our understanding of drought tolerance and enable the genetic enhancement of drought-tolerant rice cultivars. Evaluation of drought resistance is challenging due to the dynamic and highly variable timing, persistence, and intensity of drought stress in natural settings. Recent developments in functional genomics enable high-throughput genotyping, allowing for the identification of key QTLs linked to drought tolerance. Most studies on drought resilience focus on above-ground features, leaving a significant gap for below-ground traits. Studies of drought tolerance should adequately take into account root flexibility and architecture because of their important roles in controlling growth and stomata under dry conditions.

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