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Drought Stress in Rice: Effects and Management Options

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ABSTRACT

Drought stress is one of the major challenges in agriculture, particularly in rice production, and has significant negative impacts on the growth and yield of this crop. Rice, as a staple food in many countries worldwide, is highly affected by water scarcity and climate change. Drought stress induces oxidative stress and disrupts the physiological processes of the plant, ultimately leading to reduced yield and product quality. The physiological and biochemical adaptations of plants to cope with this stress include alterations in growth patterns, hormonal regulation, and the production of secondary metabolites. Furthermore, management strategies such as selecting drought-resistant varieties and improving irrigation methods are proposed to mitigate the negative effects of drought stress on rice. This study aims to develop effective strategies for water resource management and enhance rice production under drought stress conditions. The article reviews the effects of drought stress on seed germination, root growth, photosynthesis, and dry matter production in rice.

Keywords: Rice, Oxidative stress, Strategies, Germination

INTRODUCTION

Rice (Oryza sativa) is one of the most important and widely consumed food crops worldwide, playing a crucial role in feeding large populations (Cong *et al.*, 2011). With the increasing global population and the growing demand for food, improving the yield and quality of plants has become essential (Rajput *et al*., 2024; Taghavi Ghasemkheili *et al*., 2022). However, drought stress remains a major challenge for farmers due to climate change, water resource shortages, and improper watershed management. Drought stress has profound negative effects on the physiological, biochemical, and growth processes of rice (Fathi *et al*., 2024 a, b, c, d). This stress reduces soil moisture, limiting water and nutrient uptake by roots. Its impacts on seed germination, root growth, photosynthesis, and dry matter production are evident, often resulting in lower crop yields. Additionally, drought stress induces oxidative stress in plant cells, leading to cellular damage and metabolic disturbances (Santos *et al*., 2021; Shiade *et al*., 2024 a, b). Under drought conditions, plants must develop adaptive mechanisms for survival. These adaptations include changes in growth patterns, hormonal regulation, and secondary metabolite production, enabling plants to cope with unfavorable conditions (Miftahudin *et al*., 2020; Janeeshma *et al*., 2024; Mirzaei Heydari *et al*., 2024). Understanding the effects of drought stress on rice and identifying mechanisms of resistance to this stress are of great importance. Given these challenges, research into effective management strategies and the development of drought-resistant varieties can significantly improve rice yield and sustainability (Mehdiniya Afra *et al*., 2020a). Drought is one of the most significant limiting factors for plant growth worldwide, affecting nearly 25% of agricultural lands (Lesk *et al*., 2016). Rice, being one of the most water-sensitive crops, requires the highest water input among cereals (Tao *et al*., 2006; Yang *et al*., 2008). Drought conditions occur in approximately 50% of global rice-growing areas (Ndjiondjop *et al*., 2010). It is one of the most serious threats to successful rice production, as it can occur at any stage of growth. Consequently, one of the primary challenges in agriculture is to produce more food with less water (Singh, 2003; Tuyen and Prasad *et al*., 2008). This article explores the effects of drought stress on the germination, growth, and development of rice plants, as well as management strategies to mitigate the adverse impacts of this stress.

EFFECT OF DROUGHT STRESS ON RICE GROWTH

Germination

Drought stress can significantly reduce the germination rate of seeds. Studies indicate that seeds under drought stress may germinate more slowly or fail to germinate entirely. Reduced soil moisture limits the availability of water for seed uptake, leading to delayed initial growth stages (Abubakar *et al*., 2018). Under drought conditions, the reduced availability of water impedes effective water absorption by seeds, lowering germination percentages. Furthermore, seeds in water-deficient environments often require longer periods to germinate. This delay negatively affects planting and harvesting schedules. The seedlings that do germinate under drought conditions are typically weaker and less resilient, increasing their vulnerability to subsequent growth challenges (Mehdiniya Afra *et al*., 2020b).

Effects of Drought Stress on Early Growth

Drought stress often leads to a reduction in root growth, which is crucial for water and nutrient uptake. Impaired root development under drought conditions can result in deficiencies that hinder overall plant growth. Additionally, stem and leaf growth are also adversely affected under drought conditions. Plants may reduce leaf size or refrain from producing new leaves to minimize water loss through transpiration. Drought stress also alters the levels of key plant hormones such as auxins, cytokinins, and abscisic acid. These hormonal changes disrupt normal plant growth and development processes (Shao *et al*., 2008;Mehdiniya Afra *et al*., 2014).

MECHANISIMS OF PLANT ADAPTATION

Production of Secondary Metabolites

Plants under drought stress may produce secondary metabolites, such as antioxidants, that help them combat oxidative stress. These metabolites play a crucial role in maintaining cellular homeostasis by neutralizing reactive oxygen species (ROS), which are produced in response to environmental stress (Gharechahi *et al*., 2019). Plants continuously interact with their surrounding environment, adjusting their metabolic systems to improve efficiency under changing conditions. The high degree of flexibility in plant cellular processes enables them to respond effectively to environmental fluctuations such as light intensity and water availability. This flexibility is particularly evident in cellular redox processes and the production and accumulation of ROS. These molecules serve dual roles: as signaling agents in stress responses and as damaging agents when their levels are not regulated. In drought stress, metabolic imbalances can lead to the activation of enzymes like NADPH oxidase (NOX), which increases ROS production from sources like mitochondria, chloroplasts, and peroxisomes ,The accumulation of ROS triggers signaling pathways that mediate stress responses, enhancing the plant's ability to adapt and survive under drought conditions. (Wu *et al*., 2011;Mehdiniya Afra *et al*., 2017).

Root Growth

Drought stress is one of the most critical factors limiting the growth and productivity of agricultural crops, especially rice. Roots, as the primary component of the water and nutrient uptake system, play a pivotal role in the plant's adaptation to drought stress (Mehdiniya Afra *et al*., 2021; Ghadirnezhad Shiade *et al*., 2024a). Research in this area has focused on the morphological, physiological, and biochemical changes in rice roots under water scarcity. Roots are central to water and nutrient absorption. Drought stress reduces root growth, limiting the plant's ability to absorb water (Mehdiniya Afra *et al*., 2019). Under drought conditions, roots may grow toward deeper soil layers to access water. Drought stress reduces the length, volume, and number of lateral roots, due to constraints on cell division and elongation in the root meristem. Additionally, the root-to-shoot ratio (R/S) increases under drought stress, indicating a higher allocation of resources to roots for improved water absorption (Uga *et al*., 2013). Rice roots under drought stress increase the production of regulatory hormones, such as abscisic acid (ABA), which play a vital role in stomatal closure and reducing water loss. A decrease in nutrient uptake capacity, particularly phosphorus and nitrogen, has also been reported (Zhang *et al*., 2006). Drought stress enhances the production of reactive oxygen species (ROS) in roots. If uncontrolled, these species can damage cellular structures. However, antioxidant enzymes like catalase and superoxide dismutase in roots increase to mitigate this stress (Huang *et al*., 2014). Studies on genes affecting root growth, such as DRO1, have shown that genetic modifications can develop deeper, more efficient roots for water uptake (Henry *et al*., 2011;Mehdiniya Afra *et al*., 2017).

Photosynthesis and Dry Matter Production

Drought stress leads to the closure of stomata and a reduction in photosynthesis. This decline in photosynthesis directly impacts dry matter production and ultimately the yield of the crop. Additionally, drought stress can increase the production of secondary metabolites, which may act as a defense mechanism. Drought stress is one of the most important limiting factors for the growth and productivity of agricultural plants, especially in water-scarce regions. Rice (Oryza sativa L.), a strategic and water-intensive crop, is directly affected by drought stress. This stress threatens rice production by reducing photosynthetic activity, dry matter production, and ultimately grain yield (Mehdiniya Afra *et al*., 2021). One of the plant's first responses to drought stress is stomatal closure, which reduces the entry of carbon dioxide into chloroplasts and decreases photosynthesis (Chaves *et al*., 2009). Drought stress increases the production of reactive oxygen species (ROS) and leads to chlorophyll degradation, which directly affects photosynthetic capacity (Lawlor & Cornic, 2002). Water scarcity can disrupt the photosynthetic system by damaging the electron transport chain in photosystems, reducing the production of chemical energy (ATP and NADPH) (Flexas *et al*., 2006). Drought stress limits dry matter production capacity by reducing leaf growth and the photosynthetic surface area. This effect is particularly evident during sensitive growth stages of rice, such as tillering and flowering (Kato *et al*., 2008). Under drought conditions, plants direct more of their carbohydrate resources towards sustaining vital organs like the roots, which reduces the accumulation of dry matter in the aerial parts (Blum, 2011). The reduction in photosynthesis and dry matter production leads to decreased carbohydrate supply to the grains, resulting in reduced seed weight and final yield (Pantuwan *et al*., 2002).

Hormonal Regulation

Drought stress causes changes in the ratio of plant hormones such as auxins, cytokinins, and abscisic acid. These changes can negatively affect the growth and development of the plant. Drought stress is one of the most important limiting factors for plant growth and productivity, particularly in agricultural regions with dry and semi-arid climates. Rice, as one of the world's most important agricultural products, is severely affected by drought stress, which can reduce both its yield and quality. Therefore, studying the effects of drought stress and the plant's coping mechanisms, including hormonal regulation, is crucial. Rice is a plant that requires abundant water and, when faced with water scarcity, is susceptible to drought stress. This stress can lead to reduced water absorption by the roots, a decline in photosynthetic production, stunted root and shoot growth, and a reduction in the number and size of grains. In some cases, drought stress can cause cell death, reduced metabolic processes, and even decreased product quality. Physiological drought effects in plants include changes in membrane structure, reduced ionic balance, damage to proteins and enzymes, and disruption of metabolic functions (Ghadirnezhad Shiade *et al*., 2023). One of the main signs of drought in rice is a reduction in the rate of stem and leaf growth. During the reproductive phase, water scarcity can reduce the number of flowers, leading to decreased grain yield. Additionally, drought can reduce the rate of photosynthesis and degrade chloroplast structures (Cao *et al*., 2017). In response to drought stress, plants use specific hormonal systems to maintain water balance and resist adverse conditions. Hormones play a key role in regulating physiological processes and responses to stresses. Hormones such as auxins, cytokinins, abscisic acid (ABA), and gibberellins play major roles in coping with drought stress. Abscisic acid, a key plant hormone, is known to be involved in the response to abiotic stresses. Under drought conditions, an increase in ABA levels reduces stomatal opening, thereby reducing water loss through evaporation. This process helps conserve water in plant tissues and enhances drought resistance. ABA also helps regulate enzyme and protein activities in the plant, preventing damage caused by drought (Yamaguchi-Shinozaki & Shinozaki, 2006; Ghadirnezhad Shiade *et al*., 2023). Auxins, known as growth hormones in plants, are involved in cell growth and development. Under drought stress, auxin levels decrease, which may reduce root and shoot growth. However, regulating auxins can help improve drought tolerance in plants (Sah *et al*., 2016). Cytokinins are another group of hormones that regulate cell division and plant growth. In response to drought stress, an increase in cytokinin levels can help improve plant performance by preventing cell structure degradation and maintaining balance between growth and metabolism (Zhang *et al*., 2015). Gibberellins are also involved in plant development and growth. Under drought conditions, changes in gibberellin levels may lead to reduced stem growth and grain development. In some cases, reducing gibberellin levels can help plants better respond to drought and grow more effectively (Pardo *et al*., 2011).

Oxidative Stress

Drought stress leads to the production of free radicals and oxidative stress in plants. This can cause significant damage to plant cells and tissues. Oxidative stress is one of the main consequences of both biotic and abiotic stresses in rice (Oryza sativa), resulting from excessive production of reactive oxygen species (ROS). ROS includes reactive oxygen molecules such as hydrogen peroxide (H_2O_2) and superoxide (O_2^-), which can damage lipids, proteins, and DNA (Huang *et al*., 2007; Zhang & Zhu, 2012). Environmental stresses like drought increase ROS production in rice tissues, disrupting vital processes such as photosynthesis, respiration, and growth (Liu *et al*., 2015). Specifically, research has shown that ROS can cause cell membrane degradation through lipid peroxidation, accelerating the decline in photosynthetic efficiency (Zhou *et al*., 2018). Superoxide dismutase (SOD) is the first line of defense against superoxide, converting it into hydrogen peroxide. Catalase (CAT) and ascorbate peroxidase (APX) also decompose hydrogen peroxide and play a key role in preventing cellular damage (Huang *et al*., 2007; Shen *et al*., 2016). Molecules like glutathione and ascorbic acid are important antioxidants known for neutralizing ROS (Zhang *et al*., 2017b). Recent studies have shown that the regulation of genes associated with ROS can improve rice's tolerance. For instance, overexpression of the OsSRT1 gene reduces ROS levels and enhances the plant's drought tolerance (Zhang *et al*., 2017). Moreover, epigenetic regulation such as DNA methylation plays an important role in rice responses to environmental stresses (Shen *et al*., 2016). In oxidative stress conditions, rice activates physiological mechanisms like stomatal closure and accumulation of compatible metabolites like proline. These changes help maintain osmotic balance and reduce oxidative damage (Liu *et al*., 2015). When faced with abiotic stresses such as drought and salinity, rice increases ROS production, leading to oxidative damage. Rice counteracts this damage using its antioxidant systems, including enzymes like superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), which help neutralize ROS and maintain cellular balance (Xiong *et al*., 2024; Zhu *et al*., 2024). Hormones such as abscisic acid (ABA) and gibberellins (GA) play a role in regulating rice’s responses to oxidative stress. Additionally, molecules like proline and glutathione (GSH) are recognized as non-enzymatic antioxidants that maintain redox balance under stress conditions (Xiong *et al*., 2024). These stresses lead to oxidative damage, which disrupts the plant's ionic and osmotic balance. This disruption increases malondialdehyde (MDA) and hydrogen peroxide (H_2O_2) levels, leading to lipid peroxidation and protein denaturation in rice cells (Zhu *et al*., 2024). Techniques like gene editing using CRISPR/Cas9 are being explored to enhance rice tolerance to oxidative stresses. These studies aim to identify and manipulate genes involved in antioxidant systems and stress signaling pathways (Zhu *et al*., 2024). The use of external compounds like strigolactones in rice has been shown to increase antioxidant enzyme activities and improve the plant's hormonal balance against salinity stresses (Xiong *et al*., 2024).

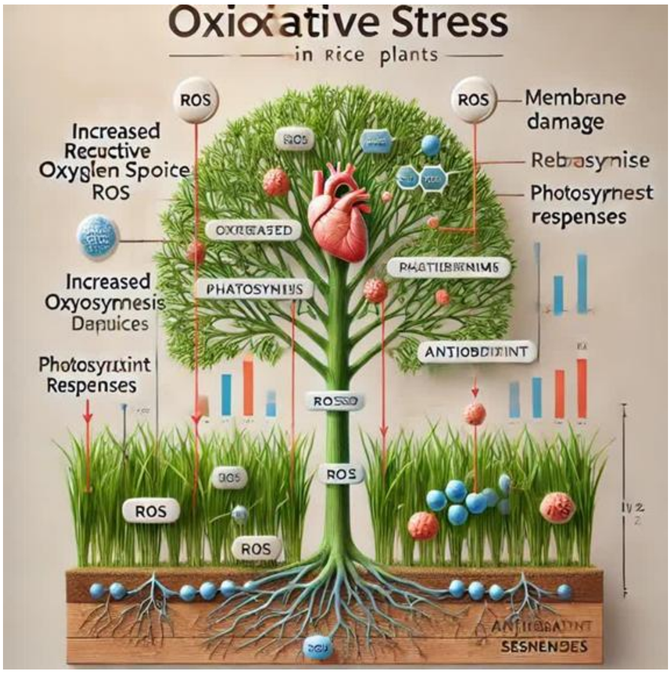

Figure 1. Effects of oxidative stress in conditions of increased free radicals

Oxidative stress in rice plants occurs when reactive oxygen species (ROS) accumulate excessively in the plant. This accumulation is often caused by factors such as drought, high temperatures, or excessive ultraviolet radiation. ROS can damage cellular structures like lipids, proteins, and DNA, leading to reduced photosynthetic efficiency and impaired plant growth. The visible symptoms of this stress in rice may include leaf yellowing (chlorosis), wilting, or a reduction in leaf surface area (Huang *et al*., 2007). The resulting oxidative damage can significantly affect the overall health and productivity of the plant.

MANAGEMENT STRATEGIES

Drought stress is one of the most significant environmental challenges in agriculture, especially in rice production. This stress reduces growth and yield, and it negatively impacts both the quality and quantity of the crop. To counter this issue, several management and technical strategies are available that can effectively reduce the damage caused by drought (Ghadirnezhad Shiade *et al*., 2024a, b; Chaves *et al*., 2011).

Selection of Drought-Resistant Varieties

One of the main strategies to tackle drought stress in rice is the use of drought-resistant varieties. These varieties are characterized by features such as tolerance to water scarcity, optimal use of water resources, and improved performance under drought conditions (Hafeez *et al*., 2023; Ghadirnezhad Shiade *et al*., 2023; Khush, 2005; Bao *et al*., 2017). In Asian countries, where rice is the primary crop, breeding drought-resistant varieties is particularly important. Research has shown that using drought-resistant rice varieties can minimize the negative impacts of drought stress. These varieties are specifically adapted to reduce water evaporation and enhance water usage under dry conditions (Manavalan *et al*., 2009; Rao *et al*., 2017).

Irrigation Management

Another important strategy is the use of efficient irrigation techniques. Pressure irrigation or low-flow irrigation systems (e.g., drip irrigation) and precise scheduling of irrigation can reduce the effects of drought stress (Bouman *et al*., 2007). Additionally, the use of smart systems for managing water consumption, especially in areas with limited water resources, is essential. One of the most effective methods for mitigating drought stress is optimal irrigation management. The use of modern techniques like drip irrigation or intermittent irrigation reduces water consumption while improving rice yield under water-scarce conditions (Sharma *et al*., 2016; Bhatia *et al*., 2020).

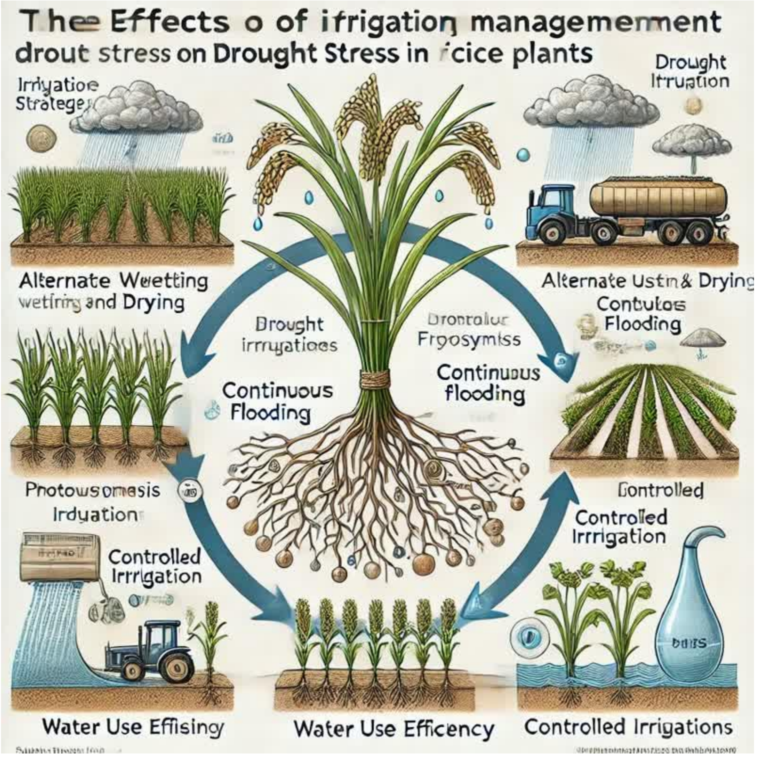

Figure 2.Irrigation management strategy and its effects on reducing drought stress

In irrigation management, various strategies can help mitigate drought stress in rice plants and improve their performance under water-scarce conditions. One effective method is Alternate Wetting and Drying (AWD), which involves periodically alternating between wet and dry soil. This approach reduces water consumption while maintaining the plant's productivity (Zhou *et al*., 2018). Compared to continuous flooding, AWD significantly lowers water use while providing rice with better drought resistance (Hafeez *et al*., 2023; Bouman et al., 2007). Continuous flooding, historically common in areas with abundant water resources, ensures good growth under normal conditions. However, under drought conditions, it can harm rice crops due to its high water demand and requires more careful water management (Pandey *et al*., 2017). Another beneficial strategy is controlled irrigation, where water application is adjusted based on the plant's needs, preventing excessive water use while ensuring the plant doesn't experience water stress. This method is particularly useful in areas with limited water resources (Liu *et al*., 2019).

Use of Chemicals and Natural Substances to Reduce the Effects of Drought

The use of both chemical and natural substances can help plants resist drought stress. Amino acids such as proline and glutamate play a significant role in mitigating the effects of drought stress. These compounds act as antioxidants, reducing oxidative damage caused by drought (Sharma *et al*., 2016; Ghadirnezhad Shiade *et al*., 2024c). Additionally, plant hormones such as abscisic acid (ABA) and auxins can help regulate irrigation processes and maintain the plant's moisture balance (Chaves *et al*., 2011; Yadav *et al*., 2018). Moreover, the use of plant extracts and nanoparticles, such as herbal extracts and nanomaterials, has been shown to improve rice's resilience to drought. These substances can enhance antioxidant systems in the plant and strengthen defensive responses against drought stress (Ali *et al*., 2020; Shiade *et al*., 2025). Additionally, nitrogen and phosphorus fertilizers can improve water absorption and photosynthesis, thereby increasing the plant's drought tolerance (Fathi, 2022; Fathi and Afra, 2023).

Mulching and Use of Plant Covers

Using mulch or plant covers in rice fields can significantly reduce water evaporation and maintain soil moisture. This method is particularly effective in areas with low rainfall, helping to alleviate drought stress (Wang *et al*., 2016). Mulching can help reduce evaporation and preserve moisture in dry soils, thus supporting rice growth (Kumar *et al*., 2018).

Nutrient Management

Proper nutrient management during critical drought periods can improve rice performance under dry conditions. The use of nitrogen and phosphorus fertilizers can help strengthen the plant's growth and resilience against drought. These fertilizers support photosynthesis and enhance water absorption, ultimately improving rice's drought tolerance (Ghadirnezhad Shiade *et al*., 2024a, b; Fathi *et al*., 2024e; Ali *et al*., 2024).

CONCLUSION

Drought stress is a major challenge in agriculture, particularly in rice cultivation, where it significantly impacts plant growth and productivity. As a water-intensive crop, rice is highly vulnerable to water scarcity and reduced water resources, leading to decreased yield and quality. Research has shown that drought stress affects rice's physiological and biochemical processes, including reduced water absorption, decreased photosynthesis, increased free radical production, and damage to cell membranes. These changes result in stunted growth and lower crop yield. To combat this challenge, several strategies have been proposed. The selection of drought-resistant varieties is one of the most effective approaches, as it can enhance plants' resistance to water scarcity. Furthermore, management techniques such as optimizing irrigation, using mulch and plant covers, and applying chemical and natural substances (such as amino acids and plant extracts) can effectively reduce the impact of drought. Fertilization, particularly under drought conditions, is also essential for promoting plant growth and improving drought tolerance. Ultimately, achieving higher productivity under drought conditions requires the combination of these strategies, and continued development of drought-resistant rice varieties. Future research can explore the optimal combination of these strategies and introduce new solutions for managing drought stress in rice cultivation.

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