Selcuk Journal of Agriculture and Food Sciences
https://dergipark.org.tr/tr/pub/selcukjafsci
Review Article

(2024) 38 (1), 169-181 DOI:10.15316/SJAFS.2024.016 e-ISSN: 2458-8377 Selcuk J Agr Food Sci

Drought Tolerance in Rice (*Oryza Sativa* L.): Impact, Performance and Recent Trends

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HIGHLIGHTS

- Rice is a primary cereal crop for over half the world's population, meeting 35-60% of their calorie needs.
- Drought is a significant environmental factor affecting rice production, particularly in Asia, impacting around 30% of farmers.
- Drought-tolerant rice varieties have been developed to enhance and stabilize rice yields, with Nepal releasing 11 such varieties.
- Understanding the types and impacts of drought is crucial for effective drought management and mitigation strategies.

Abstract

Drought poses a significant challenge to rice cultivation in Asia's rain-fed regions, which is expected to worsen with climate change. This article presents a comprehensive review of the current state of knowledge on drought tolerance in rice, based on a literature review of 52 relevant articles. The articles were chosen based on their relevance to the topic of drought tolerance in rice. The selected articles were then analyzed using a qualitative approach to summarize and synthesize their findings into three main sections: impact, performance, and recent trends. The article highlights several key findings on the development of drought-tolerant rice cultivars, including the identification of genes that control responses to water availability, the use of submergence-tolerant varieties in flood-prone lowlands, and the importance of physiological, biochemical, and molecular adaptation processes in improving rice's tolerance to drought stress. The article emphasizes the importance of marker-assisted breeding and cultivation in semi-arid and rainfed environments to develop more drought-tolerant cultivars. The development of drought-tolerant rice cultivars is crucial to ensure food security and mitigate the effects of climate change in Asia's rain-fed regions. The article also discusses various types of droughts and their effects on different plant species and drought pressures. As the global population increases, the demand for rice as a dependable food crop also rises. To meet this demand, rice cultivation must be expanded to rainfed areas. However, rice's adaptation mechanisms and habitat make it one of the most challenging crops for breeders to develop drought-tolerant varieties. Overall, this article provides important insights and recommendations to improve rice productivity and address the challenges associated with drought in rice cultivation.

Keywords: Rice; *Oryza sativa;* Drought tolerance; Stress response; Impacts; Sukhadhan

Citation: Shah B, Yadav SPS, Shrestha M, Khadka A, Dahal K, Neupane B, Bhandari S (2024). Drought tolerance in rice (Oryza sativa L.): Impact, performance and recent trends. *Selcuk Journal of Agriculture and Food Sciences*, 38 (1), 169-181. https://doi.org/10.15316/SJAFS.2024.016
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Received date: 23/06/2023
Accepted date: 22/10/2023

1. Introduction

Rice is a perennial, semi-aquatic, self-pollinated cereal crop that belongs to the Poaceae family (Adhikari et al., 2022). It is the primary cereal crop for more than half the world's population (Dar et al., 2020). Over half of the world's population consumes rice as their primary staple diet, which meets their calorie needs by 35 to 60% (Dhakal et al., 2020). Nearly every part of the world—including the tropics, subtropics, and tropical and temperate regions—now has rice-growing areas (Ji et al., 2012). Developmental nations produce most of the world's rice, with China and India alone accounting for nearly 95% of global production (Dhakal et al., 2020). According to FAO, the rice yield in 2019 was 4661 kg/ha, while the yearly output was 755473800 tons (Adhikari et al., 2022). More than 90% of the world's rice production and consumption occurs in Asia, which is superior to other continents in production and consumption (Panda et al., 2021; Vinod et al., 2019). More than half of the country's population's daily calorie needs are met by rice, a significant food crop in Nepal. It can be grown in Nepal's diverse agro-climate zones, which range from the terai (50 masl) to the mid-hills and high mountains valley (3050 masl), which is Jumla, the highest altitude of any rice-growing region in the world (Adhikari et al., 2022; Dhakal et al., 2020).

Rice contributes significantly to Nepal's agricultural GDP, aids national food security, and improves people's standard of living (Gauchan et al., 2014). Several environmental factors have reduced global rice output, particularly in the lowlands of Asia; roughly 30% of farmers have been impacted (Dar et al., 2020). In order to give nutrients and water, rice is often produced in flooded circumstances; however, due to the low water availability, around half of the rice lands have seen some reduction in production as a result of the drought (Gusain et al., 2015). About 34 million hectares of rainfed lowland rice and 8 million hectares of highland rice in Asia are under drought stress (Dar et al., 2020). Most of Nepal's rice fields are prone to drought, and around two-thirds are rain-fed (Figure 1) (Gauchan et al., 2014). Drought is one of the main abiotic variables inhibiting rice growth, development, output, and productivity and lowering rice areas (Dhakal et al., 2020; Guo et al., 2013). Therefore, disseminating these drought-prone types more widely, creating and promoting various drought-resistant rice varieties has been crucial in enhancing and stabilizing rice yields. Drought tolerance is the multifunctional outcome of many molecular, morphological, and biochemical traits (Sahebi et al., 2018). The creation of rice cultivars resistant to drought was started in the 1960s by the International Rice Research Institute (IRRI). However, hopeful outcomes did not appear until around ten years ago (Dar et al., 2020). Nepal has created and released around 11 drought-tolerant rice varieties to address productivity and food security issues with IRRI's technical assistance (Gauchan et al., 2014). Sukhadhan-1, Sukhadhan-2, and Sukhadhan-3 were published in 2011, while Sukhadhan-4, Sukhadhan-5, and Sukhadhan-6 were released in 2014 as drought-tolerant rice varieties created in Nepal. These varieties can help improve grain output and quality, leading to poverty eradication and improved health and standard of living for farmers (Dar et al., 2020; Vinod et al., 2019).

The objective of this article is to provide an overview of the importance of rice as a primary cereal crop for a significant portion of the world's population, the environmental and agricultural factors that can impact rice production, and the efforts made to develop drought-resistant rice varieties in order to enhance rice yield, productivity, and food security.

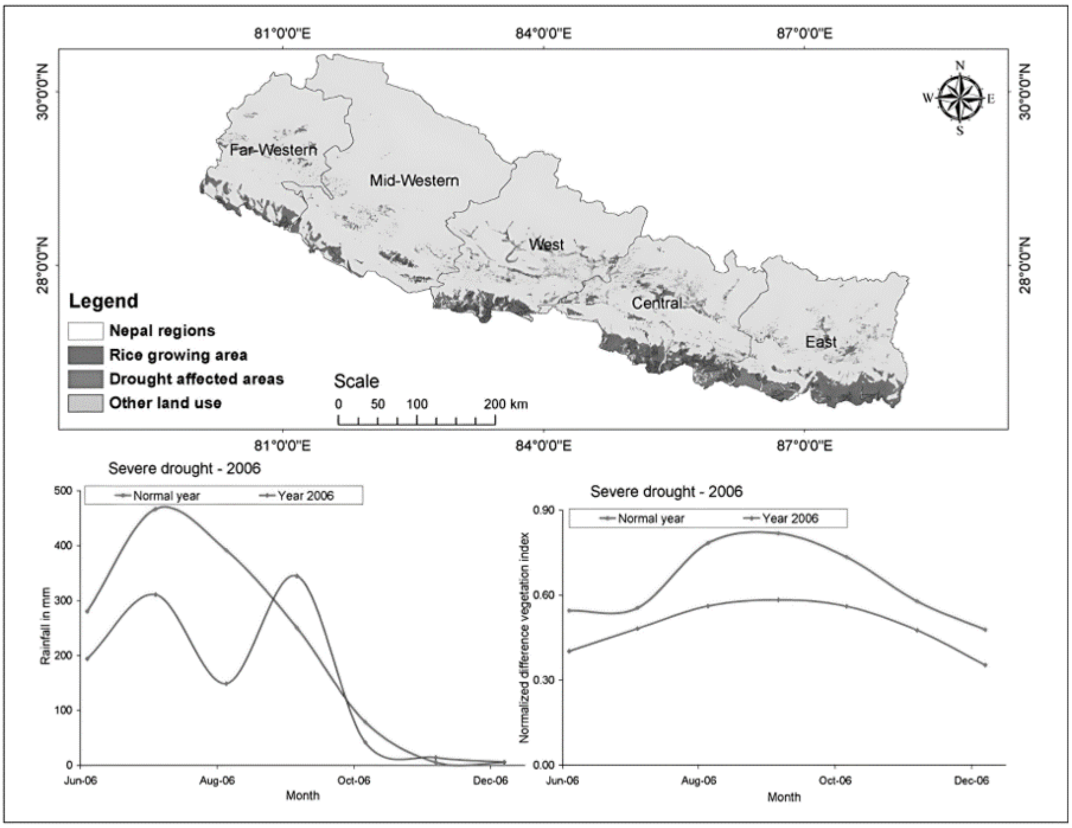

Figure 1. Geospatial mapping of drought-prone rice production locations in Nepal (Source: Gumma et al., 2011).

2. Materials and Methods

This manuscript is based on a literature review of 52 articles selected from various scientific databases. The articles were chosen based on their relevance to the topic of drought tolerance in rice (*Oryza sativa* L.) and their publication dates (from 2010 to 2022). The selection process was conducted by searching for articles using relevant keywords such as "drought tolerance," "rice," "*Oryza sativa*," "stress response," and "Impacts." The selected articles were studied for their impact, performance, and recent trends in drought tolerance in rice. These articles were then summarized in a coherent manner to provide an overview of the current state of knowledge in this field. The analysis of the selected articles was conducted using a qualitative approach, which involved summarizing and synthesizing the findings of each article. The concept and findings from the selected articles were organized into three main sections: impact, performance, and recent trends. Each section provides a detailed description of the key findings of the selected articles and their implications for the development of drought-tolerant rice varieties. Overall, this manuscript presents a comprehensive review of the current state of knowledge on drought tolerance in rice, based on a selection of 52 relevant articles.

3. Results and Discussion

3.1. Types of droughts

Drought is a complex phenomenon with significant impacts on various sectors of society. It is defined as the absence or insufficiency of precipitation, which may be measured as a decrease in precipitation quantity and can occur for a brief time or be protracted across many years (Carroll et al., 2021). Drought has become a severe global concern, and the severity of disasters like drought has significantly grown since the 1970s, with a projection of continued increase in the twenty-first century, according to the earth system model (Liu et al., 2016). The impact of drought on water supplies, agricultural output, and social activity is significant and has been studied extensively (Caloiero et al., 2021). The strength and severity of a drought may be determined through drought indicators, which are essential in assessing and analyzing the danger of drought (Aghelpour et al., 2020). Numerous research efforts have been made globally to comprehend and efficiently address drought (Bae et al., 2019). Rice plants adapt to drought stress through morphological adjustments in their root system, reducing water loss through transpiration, and accumulating osmoprotectants and antioxidants (Figure 2). They also undergo changes in gene expression to prioritize survival over growth. Understanding these mechanisms can aid in the development of strategies to improve rice plant drought tolerance. Understanding drought is crucial for effective management of water resources and related sectors. It is divided into four categories to facilitate study and research on drought: socioeconomic, agricultural, hydrological, and meteorological/climatological droughts (Wang et al., 2016). Additionally, droughts are classified into three categories based on their severity, length, and geographical distribution (Zargar et al., 2011). Overall, the study of drought is critical for the development of appropriate mitigation and adaptation strategies to address its negative impacts on society and the environment. The utilization of drought indicators can aid in effective management and preparedness to minimize drought impacts.

3.1.1. Meteorological drought

Meteorological drought, which is caused by an imbalance between precipitation and evapotranspiration, is a type of water shortage (Liu et al., 2016). This type of drought occurs due to a lack of precipitation, which may also be accompanied by an increase in potential evapotranspiration (Caloiero et al., 2021). It has been observed that non-meteorological droughts are linked to meteorological droughts, which underscores the importance of studying meteorological drought to comprehend its interplay with other types of droughts (Bae et al., 2019). The primary cause of meteorological drought is a decline in precipitation, which leads to a shortage of soil moisture, also known as agricultural drought (Liu et al., 2016). Additionally, increased evaporation at high frequency can lead to hydrological drought, while a more substantial reduction in precipitation can lead to socioeconomic drought (Liu et al., 2016). The standardized precipitation index (SPI) is a widely used indicator for studying meteorological droughts, which takes into account the variability of precipitation (Caloiero et al., 2021). Understanding meteorological droughts is crucial because they can significantly impact water resources, agriculture, and social activities. By studying meteorological droughts and their interplay with other types of droughts, policymakers and researchers can develop effective strategies to mitigate the negative consequences of droughts on society and the environment.

3.1.2. Agricultural drought

Agri-drought, also known as agricultural drought, is a type of drought that occurs when soil moisture levels are below what is needed for optimal plant growth (Liu et al., 2016). This can be caused by a lack of precipitation, low soil moisture, reduction in reservoirs, and differences between actual and potential evapotranspiration (Bae et al., 2019). The impact of agricultural drought on crops can lead to reduced yields or complete crop failure, which can further impact the environment and society (Van Loon, 2015). The severity of agricultural drought is influenced by various factors, including soil temperature, soil properties, evapotranspiration, precipitation, and the physiological and ecological traits of the crops being grown (Liu et al., 2016). Monitoring agricultural drought is essential for predicting and mitigating its impact. Various drought monitoring indices have been developed, and they can be classified into site-based and remote sensing methods. Remote sensing techniques have made it possible to accurately assess the impact of drought on crops at a larger scale, and simple agricultural drought indices can be created using this information (Liu et al., 2016).

3.1.3. Hydrological drought

A hydrological drought is defined as a water shortage that results in an imbalance in the availability of water resources, a decline in water supplies or aquifers, and reservoir depletion (Liu et al., 2016). It occurs when the amount of water demanded exceeds the amount of water available in the hydrological system (Bae et al., 2019). Hydrological droughts have a significant impact on both land and aquatic ecosystems globally, highlighting the need for drought monitoring (Van Loon, 2015). It is closely related to meteorological drought, as a lack of precipitation leads to reduced water availability in the hydrological system (Wang et al., 2016). Various indicators are used to identify and index hydrological drought, such as streamflow, groundwater levels, and lake and reservoir storage (Van Loon, 2015).

3.1.4. *Socioeconomic drought*

Socioeconomic drought is often caused by the interplay of climatic factors, resource availability, and the societal response to drought impacts. It can result in economic losses, reduced income, unemployment, increased poverty, and food insecurity, among others (Liu et al., 2016; Kundu et al., 2021). It can also cause social and political unrest, migration, and conflicts over scarce resources (Kundu et al., 2021). Therefore, understanding the socioeconomic impacts of drought is crucial in developing effective policies and strategies to mitigate and adapt to drought risks.

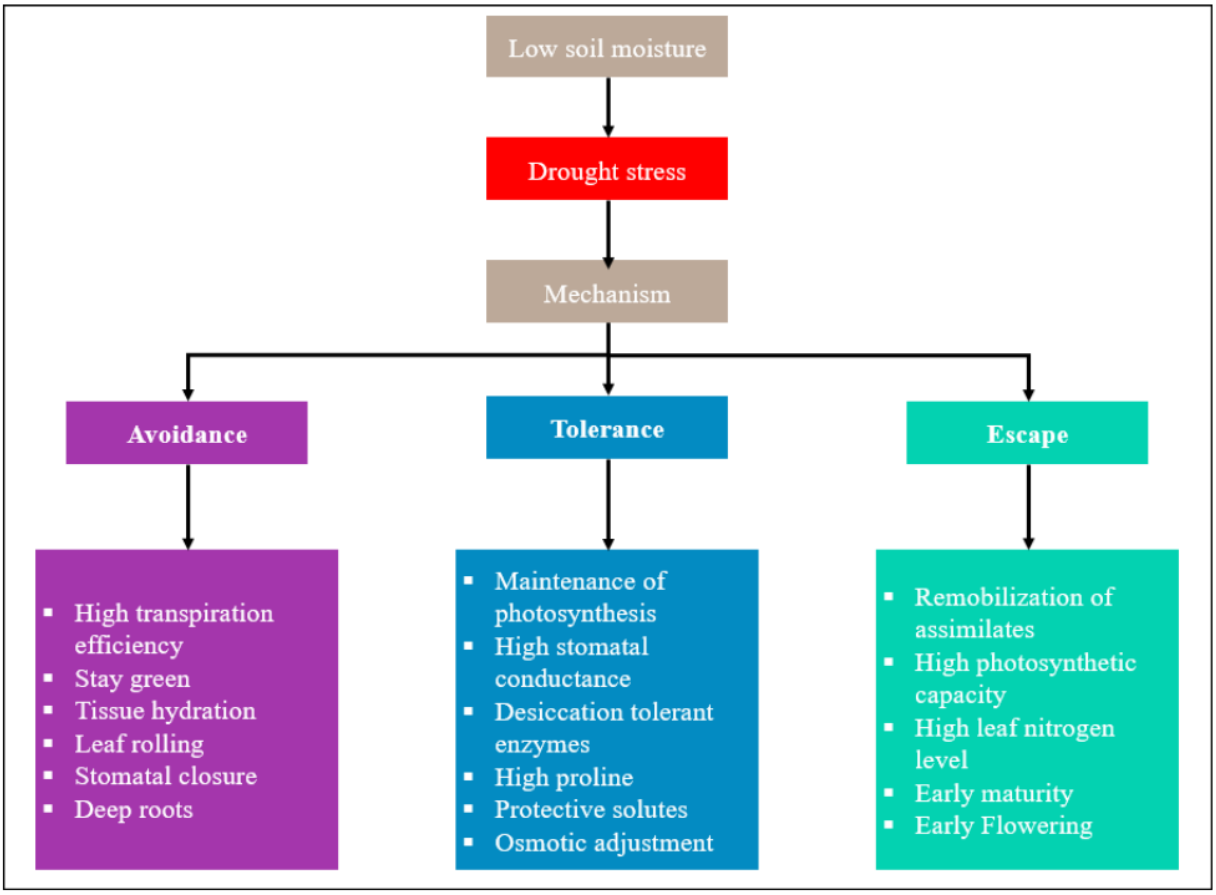

Figure 2: Mechanisms involved in rice plant adaptation to drought stress (Source: Panda et al., 2021).

3.2. *Effect of drought stress*

Plants are significantly affected by drought under abiotic stress, which is the primary factor limiting agricultural yield and ultimately determining the order of plant species. Stomata closure, decrease in water content, and drought stress are some effects that can be observed by regulating gas flow. Significant water loss can lead to the accumulation of reactive oxygen species (ROS), which disrupts metabolism and enzyme-catalyzed processes, potentially causing plant death (Hà, 2014).

3.2.1 Morphological stress

Plants exhibit a complex response to drought stress, which includes morphological changes. The most common sign of drought stress is reduced plant growth, and most plant species experience changes in leaf architecture and structure due to drought stress (Lum et al., 2014). The immediate impact of drought is impaired germination, which negatively affects standing ability (Ndjiondjop et al., 2018). Drought stress affects the whole green plant surface, and the response of plants to this stress is complex because it involves the interaction of many types of stresses affecting a plant's response at every key developmental stage over time and space (Shekhar et al., 2021). Drought stress is a severe abiotic factor that limits rice output in the rainfed and upland habitat by causing plants to produce fewer leaves per plant and smaller leaves (Ndjiondjop et al., 2018; Shekhar et al., 2021). Drought stress during the tillering phases harms the number of tillers, leaf length, and area (Shekhar et al., 2021). Under full irrigation, rice leaves typically do not roll, but during a drought, they roll in, preserving their positive internal water status. Drought is a factor in leaf rolling and burning of the leaf tips, particularly in vulnerable rice cultivars. Leaf rolling during a drought is reversible, but leaf tip drying is not (Ndjiondjop et al., 2018).

Drought stress lowers metabolic activity as a result of the lack of water. Reduced metabolic activity lowers turgor pressure, impairs the plant's cell division and elongation processes, and lowers plant height (Singh et al., 2018). The most crucial time for controlled watering and drainage may be during the vegetative stage. According to studies, the blossoming period is the most vulnerable to water scarcity (Yang et al., 2019). Grain weight may decrease due to the loss in absorption and nitrogen availability to reproductive plant parts brought on by drought stress. Under drought stress, yield/plant was substantially correlated with plant height, panicle length, grains/panicle, and grain weight/panicle (Bhutta et al., 2019). Drought stress impacts plant height, the number of tillers, and panicles during the vegetative stage. The elongation of the cell is constrained during drought stress, which shortens the internode's length and causes a drop in plant height (Haque et al., 2016). Raising root weight under water stress may be an adaptive process that lowers water intake owing to more root development during dry circumstances (Davatgar et al., 2009). At the vegetative drought stage root, the dry matter often declines, and forcing a drought during blooming resulted in almost the same reaction. Studies show drought stress inhibits root development (Haque et al., 2016). Water stress is often responsible for reductions in the fresh and dry weight of leaves and shoots, chlorophyll a, b, and photosynthetic pigments, and carotenoids that impact photosynthesis. In rice, a reasonable tolerance to shoot dryness was found (Usman et al., 2012). Stunting is the most crucial morphological result of drought stress (Piveta et al., 2021).

3.2.2 Physiological Stress:

Drought is a significant environmental stress that can have a detrimental impact on crop yield and plant development in large agricultural areas (Saha et al., 2019). Plants exhibit various physiological responses to changes in their water status and adapt to their surroundings. One of the first indications of water scarcity in rice plants is a decrease in growth. In response to drought stress, plants may develop additional aerial organs. This is accompanied by changes in the physio-chemical characteristics of cell walls and a decrease in the rate of cell division. When tissue water status decreases, the stomata close to reduce the transpiration rate, thereby conserving water in the plant (Ndjiondjop et al., 2018). Water stress during the blooming stage leads to a higher proportion of empty grains due to reduced carbohydrate synthesis, weakened sink strength, and fertilized ovary abortion. Furthermore, terminal drought stress during grain filling leads to a reduction in kernel mass and size, which results in chalky grains. This occurs due to loosen starch packing in the endosperm, which lowers grain production and mass (Kumar et al., 2020). Stomatal closure, reduced gas exchange, and increased water stress can lead to the accumulation of reactive oxygen species (ROS). Rice seedlings may exhibit severe drought symptoms due to a decrease in chlorophyll content and an increase in H2O2 and malondialdehyde (MDA) in response to drought stress (Hà, 2014).

Drought stress can reduce photosynthetic activity due to stomatal or non-stomatal processes. Stomatal closure, which is the initial response to drought stress, results in a reduction in photosynthesis and a disruption of critical photosynthesis-related processes, including CO2 supply, electron transport in thylakoids, peroxidative degradation of lipids, and water balance (Anjum et al., 2011). Drought stress can also result in an increase in proline buildup, which provides osmotic adjustment to defend cell turgor. Proline can also support enzyme protein stability and cell membrane integrity (Patmi et al., 2020). Drought stress reduces photosynthetic pigments and carotenoids, leading to a decline in leaf photosynthetic rate (Usman et al., 2012). Under restricted drought circumstances, physiological characteristics such as relative water content, leaf water potential, stomata conductance, transpiration, and leaf temperature are altered. Reactive oxygen species (ROS) damage to chloroplasts due to drought stress is associated with a decrease in chlorophyll content (Piveta et al., 2021).

3.3. Drought toleract rice varieties

In rain-fed regions of Southeast Asia, drought is a major environmental stress that reduces rice productivity across more than 24 million hectares of land, as noted by Adhikari et al. (2019). To address this challenge, the International Research Rice Institute (IRRI) has developed drought-tolerant rice varieties that offer better performance and higher yields to help ensure food security in regions that are prone to drought, as reported by Dar et al. (2020). One such genotype developed by IRRI is the breeding line IR74371-70-1-1, which has been distributed under the names Sahbhagi Dhan in India, Sukhadhan in Nepal, and BRRI Dhan in Bangladesh, and has shown promising results in withstanding drought stress, as reported by Anantha et al. (2016).

3.3.1 Sukhadhan Varieties in Nepal

With the assistance of the International Research Rice Institute (IRRI), Nepal has developed and released nine drought-tolerant rice cultivars, including the Sukhadhan series (Sukhadhan-1,2,3,4,5,6) (Gauchan et al., 2022). Sukhadhan-1, 2, 3, and Sukhadhan-4,5,6 were released in 2011 and 2014, respectively (Adhikari et al., 2019). The Sukhadhan series has varying maturation periods, with Sukhadhan-1 taking around 125 days to mature, followed by Sukhadhan-2, Sukhadhan-3, Sukhadhan-4, Sukhadhan-5, and Sukhadhan-6 maturing in about 120–125 days. Among the Sukhadhan series cultivars, Sukhadhan-5 has the highest yield of approximately 3.2–4.2 tons/ha, while Sukhadhan-3 performs well under drought-like conditions (Gauchan et al., 2022). Sukhadhan-2, Sukhadhan-5, Sukhadhan-3,4 (76 grains), Sukhadhan-1 (75 grains), and Sukhadhan-6 (68 grains) have been identified as the cultivars with the most effective grains per panicle under drought conditions (Dhakal et al., 2020). This series of drought-tolerant Sukhadhan rice cultivars shows promising potential for replacing older rice varieties in both irrigated and drought-prone areas, as they produce higher yields under varying water conditions (Adhikari et al., 2019).

3.3.2 Sahbhagi Dhan in India

In 1997, IR55419-04 and "Way Rarem" were crossed to produce the drought-tolerant and high-yielding Sahbhagi Dhan rice variety (Anantha et al., 2016). It was introduced by the Central Rain-fed Upland Rice Research Station of India in 2009 as an early-duration drought-tolerant variety (Dar et al., 2020; Rai et al., 2020). Research conducted in Eastern India demonstrated that Sahbhagi Dhan has the most consistent yields and outperforms other rice varieties (Dar et al., 2020). Sahbhagi Dhan was created to thrive in drought-prone areas of India and has a yield advantage of 0.5 to 1 ton/ha over other rice varieties during droughts (Kumar et al., 2021). Although it is resistant to leaf blasts, it is only moderately resistant to brown spots, sheath rot, stem borer, and leaf folder. Sahbhagi Dhan matures in approximately 105 days and produces an average yield of 4 to 5 tons/ha (Rai et al., 2020). By allowing early access to food, increasing cropping intensity, attracting better markets, reducing input costs, improving grain quality, and enhancing grain resistance to pests and diseases, Sahbhagi Dhan has enabled farmers to increase their yields and free up labour resources (Dar et al., 2020).

3.3.3 BRRI Dhan in Bangladesh:

The Bangladesh International of Nuclear Agriculture (BINA) developed a series of drought-tolerant rice varieties, which include BRRI dhan-55, BRRI dhan-42, BRRI dhan-43, BRRI dhan-48, BRRI dhan-33, BRRI dhan-56, BRRI dhan-57, BRRI dhan-66, BRRI dhan-71, and BRRI dhan-83 (Shelley et al., 2016). These varieties have demonstrated superior yield potential and exhibit reasonable resistance to leaf blight and sheath blight (Rahman et al., 2021). Among these varieties, BRRI dhan-55 has the highest average yield potential of approximately 4 tons/ha (Shelley et al., 2016). Furthermore, under drought conditions, BRRI Dhan-56 and BRRI Dhan-57 have demonstrated a yield potential of around 4-4.5 tons/ha and have been reported to outperform other rice varieties in Bangladesh (Rahman et al., 2021).

3.4. Impacts of Sukhadhan

Sukhadhan, a rice variety preferred by farmers in areas with lower water supply, has been found to be able to thrive without constant irrigation supply, which is a significant benefit in rain-fed environments where drought stress can harm plant function and result in complete crop failure and lower output. Tripathi et al. (2012) reported that Sahbhagi Dhan, a type of Sukhadhan, has an increased average grain production, particularly under drought conditions, and its early maturing characteristics allowed farmers to increase cropping intensity effectively, accommodating supplementary short-duration crops in the present cropping system. Furthermore, Kar et al. (2018) found that Sahbhagi Dhan produces uniform average grain weight in all water systems when used in DSR (direct-seeded rice), unlike other cultivars, whose grain weight significantly decreased at either 10 kPa or 40 kPa. Additionally, Anantha et al. (2016) observed that Sahbhagi Dhan can compete with weeds and sustain more substantial plant populations under stress compared to other recently produced rice varieties under direct dry seeding due to its high seedling emergence leading to early vegetative development, combined with its semi-tall height. Studies have also shown that the semi-dwarf plant type of Sukhadhan-3 responds well to production inputs, including fertilizer and watering (Deo et al., 2019), while Sukhadhan-5, which had the greatest CGR and maximum LAI, significantly increased photosynthetic rate and accumulation (Mahato & Adhikari, 2017). The highest photosynthesis efficiency is found in low-lying sections of rice, indicating that as altitude increases, photosynthesis efficiency tends to decrease (Li & Lin, 1993; Dhakal et al., 2020). Although Sahbhagi Dhan showed several positive traits for responding to drought, it also demonstrated several negative traits. Its vegetative development is comparably weak during dry seasons owing to low temperatures or low solar exposure, as opposed to other genotypes that lack lateral root response to drought (Anantha et al., 2016). Moreover, its performance in experiments under lowland drought was observed to fluctuate for midseason shoot biomass under vegetative stage stress owing to varying climatic circumstances compared to other genotypes (Anantha et al., 2016). Adopting Sahbhagi Dhan may result in lower input and labor costs along with an increase in yield and cropping intensity. However, there is no quantitative data to support these claims, which bring behavioural reactions to bear in managing risk, household habits, and investing (Dar et al., 2020). Sukhadhan also offers a greater byproduct, such as straw used to feed animals, and closer spacing results in a high rate of tillers per unit area, which is the cause of the highest byproduct output (Dhakal et al., 2020).

3.5. Ongoing campaigns to raise awareness of drought-tolerant rice plants

Climate change scenarios are expected to worsen the drought vulnerability situation for rice cultivation in rain-fed regions of Asia, which is already a major challenge for farmers (Serraj et al., 2011). In response, researchers have been exploring genomic-based methods to increase drought tolerance in rice by identifying genes that control molecular, cellular, and developmental responses to water availability (Tuberosa & Salvi, 2006). Additionally, in flood-prone lowland areas with heavy rainfall and locations susceptible to flooding, submergence-tolerant varieties like sub-A have helped to ensure food security (Ismail et al., 2013). Physiological, biochemical, and molecular adaptation processes are also being studied to improve rice's tolerance to drought stress, including morphological responses, seed germination, seedling development, leaf and root characteristics, physiological response, leaf photosynthesis, and osmolyte buildup (Panda et al., 2021). Different novel strategies have been developed to develop drought tolerant rice varieties and to improve drought stresses (Figure 3). In Nepal, researchers commonly use polyethylene glycol for in vitro testing of rice genotypes for drought resistance. In one study, mature embryos of three aromatic Indica rice types and one non-aromatic variety were used to develop callus and test for drought tolerance (Joshi et al., 2011). Overall, these efforts aim to develop rice varieties that can better withstand drought and submergence stress to ensure food security and mitigate the effects of climate change in Asia's rain-fed regions.

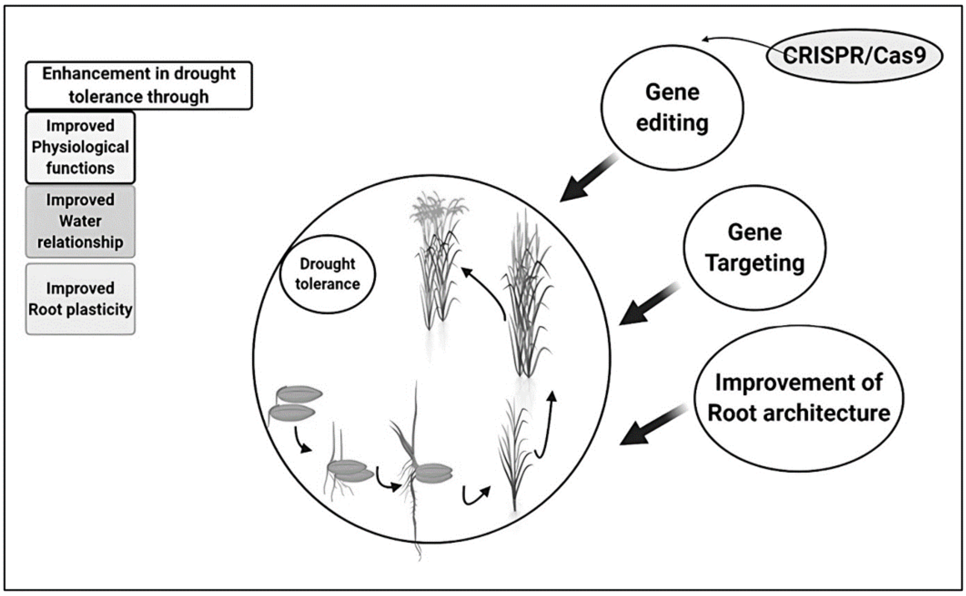

Figure 3: Novel techniques for improving drought resistance in rice plants (Source: Rasheed et al., 2020).

4. Conclusions

In conclusion, the increasing incidence of drought caused by climate change poses a significant challenge to rice cultivation in Asia's rain-fed regions. This article highlights several significant advances in the development of drought-tolerant rice cultivars. These include the identification of genes that control responses to water availability, the use of submergence-tolerant varieties in flood-prone lowlands, and the importance of physiological, biochemical, and molecular adaptation processes in improving rice's tolerance to drought stress. To develop more drought-tolerant cultivars, marker-assisted breeding and cultivation in semi-arid and rainfed environments are essential. Furthermore, to better understand the effects of drought tolerance on rice performance and to identify new trends in rice cultivation, further research is needed. Overall, these efforts are essential to ensure food security and mitigate the effects of climate change in Asia's rain-fed regions. The article's key findings demonstrate that Sukhadhan, a drought-tolerant rice variety, can thrive without constant irrigation supply, and its early maturing characteristics allow for increased cropping intensity. The use of submergence-tolerant rice varieties, such as sub-A, has been critical in ensuring food security in flood-prone lowlands. Developing drought-tolerant rice cultivars requires identifying genes that control responses to water availability, physiological, biochemical, and molecular adaptation processes, and marker-assisted breeding and cultivation in semi-arid and rainfed environments. Additionally, further research is necessary to assess the effects of drought tolerance on rice performance and to identify new trends in rice cultivation.

Author Contributions: The authors contributed equally to work reported.

Conflicts of Interest: The authors declare no conflict of interest.

Funding: This research received no external funding.

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