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Advancements in Rice Biotechnology for Enhanced Abiotic Stress Tolerance

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Rice (*Oryza sativa* L.) is a vital crop globally, crucial for food security. However, its production faces increasing challenges from abiotic stresses such as drought, cold, heat, salinity, and heavy metals, exacerbated by climate change. This review explores biotechnological approaches aimed at enhancing rice's resilience to these stresses. Key strategies include genetic engineering for introducing stress-tolerant genes, modification of regulatory pathways involved in stress response, and enhancement of physiological adaptations. Advances in biotechnology offer promising avenues for developing rice varieties with improved tolerance to abiotic stress, thereby ensuring sustainable production in diverse agricultural environments.

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1. INTRODUCTION

"Rice (*Oryza sativa* L.) is a staple cereal crop that feeds half the world's population. Although rice can be grown all over the world, Asian countries account for more than 50% of the total output" [1,2]. "It is a member of the Poaceae family, specifically the genus *Oryza*, which comprises 24 species—22 wild and 2 cultivated" [3]. "Among the cultivated species, *O. glaberrima* and *O. sativa* are well-known, originating from regions across Asia, Europe, the United States, and Africa" [4]. "*O. sativa* is the most widely cultivated rice species due to its adaptability to various regions. It is classified into *japonica*, *indica*, and *javanica* varieties" [4]. *Indica* and *japonica* types are predominantly grown in tropical, subtropical, and temperate regions, while *javanica* is a less common variety adapted to hot and humid conditions.

"Abiotic stressors influence plant development and growth rate at the physiological and biochemical levels, which are essential for increasing crop product efficiency, resulting in losses in yield in the agricultural sector worldwide" [5]. "Different environmental components, such as drought, salinity, heat, cold, and heavy metals, are regarded as important abiotic stresses affecting rice plants. The duration and progression of stress, various stages of plant growth and development, and biotic and abiotic factors may all influence the response to abiotic stresses" [6].

Rice production is significantly affected by diverse abiotic stresses, but these challenges can be mitigated by leveraging genes and regulatory networks from stress-tolerant rice cultivars and other plant species. These genetic resources are instrumental in developing new rice cultivars (see Fig. 1).

Abiotic stresses can activate a diverse array of genes, and intricate transcriptional networks regulate the expression of stress-tolerant genes. Molecular techniques are employed to investigate key genes within these networks, facilitating the development of transgenic rice varieties that are tolerant to abiotic stresses [7]. As a result, several biotechnology technologies are applied to create rice cultivars that are resistant to abiotic stresses (Table 1).

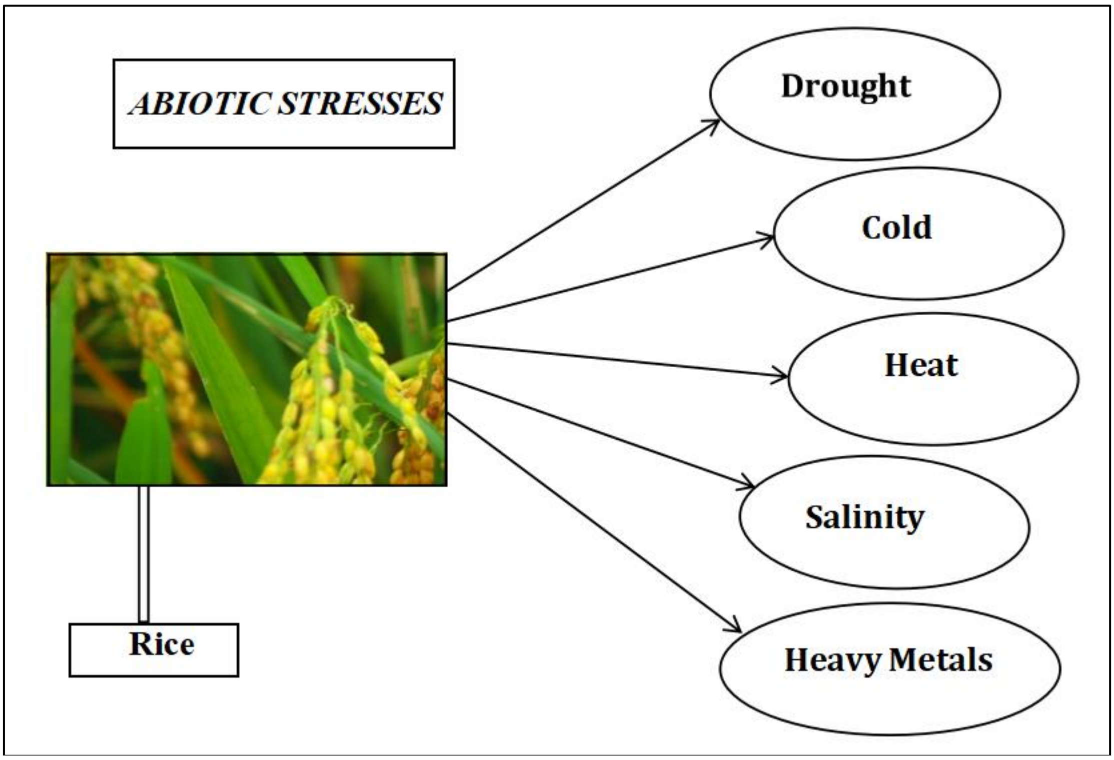

Fig. 1. Common abiotic stresses affecting Rice crop

Table 1. Some transgenes are inserted to improve the abiotic stresses [8]

S. No.	Transgene(s)	Improved Traits(s)	References
1.	OsMAPK44	Drought and salinity stress tolerance enhanced	[9]
2.	OsHsp101, AtHsp101	Heat stress tolerance enhanced	[10]
3.	HvCBF4	Salinity, drought and cold tolerance capacity enhanced	[11]
4.	OsDREB1F	Salinity, drought and cold tolerance capacity enhanced	[12]
5.	OsPIP1;3	Cold stress tolerance ability enhanced	[13]
6.	Choline mono-oxygenase	Heat and salinity stress tolerance enhanced	[14]
7.	AVP1, SsNHX1	Improved ROS and salinity stress tolerance	[15]
8.	OsSBPase	Improved photosynthetic efficiency and heat tolerance ability	[16]
9.	ZFP245	Improved ROS, cold and drought stress tolerance	[17]
10.	OsHMA3	Enhanced drought and submergence stress tolerance	[18]
11.	SUB1A	Enhanced submergence tolerance	[19]
12.	STAR1, STAR2	Enhanced tolerance to Aluminum toxicity	[20]
13.	P5CSF129A	Salinity stress tolerance enhanced	[21]
14.	Isoflavone reductase	Salinity stress tolerance enhanced	[22]
15.	OsMAPK2	Tolerance to phosphate deficiency	[23]
16.	OsMYB55	Heat stress tolerance enhanced	[24]
17.	OsNAC5	Salinity, drought and cold tolerance capacity enhanced	[25]
18.	OsLEA3-2	Salinity and drought tolerance capacity enhanced	[26]
19.	PCK, PPDK	Improved ROS stress tolerance	[27]
20.	OsETOL1	Enhanced submergence stress tolerance	[28]
21.	OsMYB48-1	Salinity and drought tolerance capacity enhanced	[29]
22.	VrDREB2A	Increased tolerance to salinity and drought stress	[30]
23.	TaMYB3R1	Enhanced drought and salt stress tolerance	[31]
24.	CaPUB1	Enhanced cold stress tolerance	[32]
25.	OsLEA4	Enhanced drought, salt and heavy metal stress tolerance	[33]
26.	OsNAC2	Enhanced drought and salt stress tolerance	[34]
27.	OsGS	Improved ROS and drought stress tolerance	[35]
28.	TsPIP1;1	Enhanced salinity stress tolerance	[36]
29.	RhMYB96	Enhanced salt tolerance	[37]

2. ABIOTIC STRESSES AFFECTING RICE CROP

2.1 Drought Stress

"Drought has been affecting agricultural land worldwide for a few years. Many molecular, physiological, and metabolic changes occur in plants due to drought stress that damages their growth and development" [38]. "During drought stress, plants respond variously and express changes in physiology and morphology. Rice drought resistance is achieved by four procedures that are (a) avoidance: avoiding contact with stress, (b) escape: changing life-cycle, (c) recovery: vegetative growth potency and (d) tolerance: nullifying the impacts of stress. Plants can survive extended periods of drought and even reproduce in areas with limited water supplies by maintaining physiological activities. These mechanisms include reduced leaf area, leaf rolling, senescence of older leaves, increased root proliferation, dense root system, scavenging reactive oxygen species (ROS), early flowering, osmotic adjustment, stomatal closure that minimizes water loss, changes in the elasticity of cell wall, and maximum uptake of deep water" [39]. Drought stress tolerance in plants can be achieved by accumulating inorganic and organic substances such as proline, potassium ions, glucose, and sucrose. This mechanism, known as osmotic adjustment, keeps the osmotic potential lower inside plant cells than outside, which allows plants to maintain their turgidity and prevent water loss.

2.2 Cold Stress

"A significant environmental component that has an impact on the development and growth of the rice crop is cold stress. A sudden decrease in temperature may influence the development of chlorophyll during the seedling stage" [40]. "The damage to rice seedlings due to cold stress ultimately decreases the grain yield. So, cold stress is a major limitation that can be overcome by using cold-tolerant rice varieties" [41]. "Because rice crops evolved in tropical regions, it has limited adaptability to chilling stress. Rice cultivation in northern latitudes is made possible by improving rice varieties to make them more cold-tolerant. Chilling tolerance is controlled through many signal transduction pathways and genetic networks" [42]. "In *japonica* rice, chilling tolerance is achieved through interactions between rice G-protein α-subunit 1 (RGA1) and chilling tolerance divergence 1 (COLD1), followed by calcium signaling initiated in the response of the downstream network of stress response that is associated with C repeat binding factor (CBF), a transcription factor" [43]. "However, there is limited information available on the stress response and adaptation. Due to its developmental plasticity, the plant responds to aberrant environmental temperatures by changing its gene expression and adapting to the desirable architecture. Cold stress can disrupt inherent signals in SAMs (shoot apical meristems), and stress tolerance can be increased by regulating the dormancy cycle at the SAM" [44]. "The survival mechanism against cold stress requires the sacrifice of niche forms of root stem cells" [45].

The differentiated cells are well-organized, and this restored development maintains meristematic activity in response to cold temperatures. During cold stress, several particular genes, such as *OsMYB3R-2*, are activated through various transcription factors to maintain mitotic cells and cold tolerance. Survival and growth have been enhanced by maintaining cellular activity and cell function during and after cold stress.

2.3 Heat Stress

"Heat stress is a key limiting factor in agricultural productivity around the world due to global warming. There is a negative correlation between higher temperatures and yields of crops, especially for rice, wheat, barley, and maize" [46]. "Heat stress can severely damage rice plants by decreasing metabolic activity, seed setting, plant growth, and pollen fertility, resulting in reduced rice production" [47]. "Excessive heat can also affect plants' photosynthetic abilities, water use efficiency, seed weight, grain mass, and leaf area. Heat stress can cause damage during both the vegetative and reproductive stages, from sprouting to maturity. However, flowering and booting are the two more essential stages that might result in complete sterility in rice cultivars" [48]. "Heat tolerance refers to plants that are capable of resisting high temperatures while lessening stress and giving enough economic yields. Rice, like other plant species, has genetic variations that help it survive heat stress. Tolerance can be achieved by altering several molecular, morphological, and physiological characteristics in rice cultivars. High temperatures increase the expression of stress-tolerating genes and metabolite reaction, beneficial for plant stress tolerance" [49]. "During heat stress, plants carry out multiple types of responses, including avoidance, survival, and escape. These mechanisms enforce avoidance over the short term and develop resistance for long-term survival. At the cellular level, stress can be controlled by several factors and methods, including transcriptional control, antioxidant defense, osmolytes, late embryogenesis abundant (LEA) proteins, and signaling cascade factors. In high temperatures, yield decreases due to early maturity, resulting in comes under the domain of avoidance strategies when it is suffering from heat stress" [48].

2.4 Salinity Stress

"Rice crops are highly vulnerable to salt stress, and approximately one-third of the world's agricultural land is impacted by salinity. The presence of excessive salts in both soil and water detrimentally affects rice production. Rising sodium ion levels in agricultural lands pose a growing threat to global agriculture. This issue causes plants to experience osmotic stress from salt accumulation outside the roots and ionic stress from salt build-up inside the plants" [50]. "The increase in food supply must be equivalent to the rate of increase in population, and this requirement must be satisfied by maximizing the utilization of all available land resources. Therefore, it is also required to enhance the productivity of saline soils. To increase saline soil productivity, different methods such as agronomic adjustments, reclamation, and biological additives are used in combination. Employing genetically improved, salinity-tolerant crop varieties is the best option for achieving sustainable crop production in these regions" [51]. "To develop salt-tolerant crop varieties, it is crucial to evaluate the genetic diversity of crops for salinity tolerance. Molecular mapping techniques have enabled the identification of genomic regions responsible for salt tolerance, making it easier to assess the genetic diversity of various crops and varieties" [52]. "Various molecular mapping techniques can identify the chromosomal regions (QTLs) responsible for salt stress tolerance in rice. Salt stress adversely affects the physiological, morphological, and biochemical characteristics of rice, negatively impacting plant height, shoot dry weight, total tillers, total dry matter, and root dry weight. The physiological attributes affected by salt stress include senescence, uptake of calcium, sodium, and potassium ions, total cation uptake, osmotic potential, transcription efficiency, and relative growth rate" [53]. "Salt stress impacts several biochemical features of rice, including proline content, anthocyanins, peroxidase (POX) activity, calcium content, sodium content, potassium content, chlorophyll content, and hydrogen peroxide content" [50].

2.5 Heavy Metals

The rhizosphere contains numerous solutes essential for plant growth and development. Plants absorb these solutes through their roots, which then distribute them throughout the entire plant. Successful plant life relies on roots taking up water and other components from the rhizospheric soil. Water uptake, along with soluble elements, drives the developmental plasticity and physiological activity in plant roots. The uptake and distribution of these inorganic materials within plants are fundamental to energy and material fluidity. In plant cells, essential ions support various physiological and structural functions. However, if these ions are present in non-physiological concentrations, they can become limiting factors. The availability of these ions to plants, disparities in their soil abundance, and their uptake rates affect cellular homeostasis. Plant defense systems and adaptations depend on developmental and physiological changes triggered by ion toxicity, which can also cause permanent damage. The rhizospheric soil also contains heavy metal ions that roots can absorb along with water and nutrients, incorporating them into plant tissues. Toxic metals for plants include zinc, iron, manganese, copper, aluminum, chromium, cadmium, cobalt, lead, arsenic, nickel, and molybdenum [54].

In polluted areas, the concentration of metal ions is excessively high, causing plants to suffer from metal toxicity. Some soils, such as serpentine soils, naturally contain high levels of heavy metals, while mining activities also contribute to elevated heavy metal content in the soil. Environmental pollutants, including high concentrations of heavy metals, are becoming a significant challenge for all organisms—plants, animals, and microbes—worldwide.

3. RICE BIOTECHNOLOGY UNDER CLIMATE CHANGE CONDITIONS

Abiotic stresses frequently arise from climate change. The impact of these stresses on plant development and yield is evident amidst the changing ecological effects of climate variations [55]. This poses a significant concern for crop production, which has recently increased due to the rapidly rising human population competing for environmental resources [56]. Agriculture, especially rice production, is susceptible to climate change [57]. Abiotic plant stress, encompassing environmental factors like drought, cold, heat, salinity, heavy metals, etc., can ultimately result from severe climatic changes, posing risks to rice crops. Under severe climatic conditions, plants may experience multiple stresses simultaneously, such as drought and high temperatures, creating unique and unpredictable stress conditions that cannot be anticipated from individual stresses alone [58].

While plants can adapt to changing climatic conditions [59], the simultaneous impact of multiple stressors resulting from frequent climate changes can lead to complete crop failure. A particular environment may be suitable for one plant genotype but can impose various abiotic stresses on another genotype with a different adaptive response [60].

4. CONCLUSIONS

The application of biotechnological tools holds immense promise for addressing the challenges posed by abiotic stresses in rice production. Genetic engineering has shown significant potential in enhancing stress tolerance through the incorporation of stress-responsive genes and the manipulation of regulatory networks. Furthermore, advancements in understanding the physiological mechanisms underlying stress responses offer opportunities for targeted modifications that can improve rice resilience to drought, cold, heat, salinity, and heavy metals stresses. Continued research and development in rice biotechnology are crucial for translating these advancements into practical solutions that ensure sustainable and resilient rice cultivation in the face of evolving environmental conditions.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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