REVIEW ARTICLE Indian Journal of Agricultural Research, Volume 58 Issue 5: 737-743 (October 2024)

Occurrence of Abiotic and Biotic Stress Tolerance in Rice: A Multigene Approach

Manjulata Palei[1], Monalisha Das Mohapatra[1], Madhusmita Pradhan[1], Ranjan Kumar Sahoo[1] 10.18805/IJARe.A-6243

ABSTRACT

A sustainable food system ensures food security and nourishment for future generations. Rice (*Oryza sativa* L.) requires emergence stress tolerance for successful cultivation in germination and early establishment stages. According to the FAO (Food and Agriculture Organization) study, rice is one of the most important worldwide cereal crops and a staple food for more than half of the world's population. Over the past few years, drastic climatic changes have been subjected to many abiotic and biotic stresses. Global estimates express that a total of 1000 million hectares of cultivated land is affected by abiotic and biotic stress. Besides this around 30% of the irrigated land area is also disturbed. This review discusses the mechanisms of stress-tolerant variants and understanding the recent developments of complex tolerance phenomena. Here, we have compiled the logical pieces as evidence of successful applications of potent molecular tools for boosting stress tolerance in rice, their prospects and limitation. This information would help researchers better understand the genetic enhancement of stress tolerance in rice.

Key words: Abiotic stress, Food security, Molecular mechanism, QTL, Rice.

Rice is the world's major staple cereal crop and feeds over half of the world's population. It is also an essential security food crop, covering 60% of World food consumption. Climate change affects crop production through exposure to different biotic and abiotic stresses. Approximately 70% of crop yield is lost due to these stresses (Sahoo *et al*., 2014). Farmers of India produce an average of 5 tonnes/ha of rice, whereas the normal yield potential is 10 tonnes/ha. This difference in yield is due to different stresses. Many countries have developed and adopted stress-tolerant rice varieties to reduce production losses (Bairagi *et al*., 2021). The production rate of rice, a major food for millions of people worldwide, is hindered by environmental stresses, resulting in a potential yield reduction of 10-15%. The abiotic stresses that affect rice crops include a range of factors such as salinity, drought, Flooding, harmful radiation, heavy metals and high temperatures. These factors lead to physiological, biochemical and morphological changes in the rice crops, ultimately reducing rice productivity worldwide (Table 1). In addition, biotic stresses like (GM) gall midge, (BPH) blast, brown plant hopper and (BLB) bacterial blight also play an important role in decreasing the quality and productivity of rice grains (Table 2). Addressing these stress factors is critical to ensure sustainable rice production and meet global food demands (Fig 1). The frequencies of both droughts and floods are likely to increase due to increased irregular rainfall patterns and harsh weather occurrences. Additionally, high temperatures can damage rice production by affecting growth and development, particularly during pollination. High temperatures can impact rice growth and development at any stage, especially during pollination. These harmful consequences can be efficiently addressed by plant breeding. Over the past few decades; rice breeding has achieved remarkable success, especially in regions conducive to crop growth. In 1970, modern high-yielding (HYVs) varieties gained rapid acceptance in irrigated and lowland areas with suitable rainfall. These kinds were less effective in regions with inadequate water management and adverse soil conditions, leading to low production and forcing farmers to continue farming low-yielding crops. During this time, breeding for abiotic stress resistance proliferated. Despite the wide adoption of HYVs (high-yielding varieties) in irrigated and rainfed areas and their widespread coverage in most tropical Asian production areas, the existing rice varieties remain insensitive to substantial abiotic stressors, further intensified by climate change. Among these challenges include salinity, submergence and drought, which are the most prevalent, reducing yields across millions of hectares in rice production areas. The limited impact of modern high-yielding rice varieties in unfavourable rainfed environments has led to the development of rice types that resist abiotic stressors like high temperature, salinity, drought

[1]School of Biotechnology, Centurion University of Technology and Management, R.Sitapur-761 211, Odisha, India.

Corresponding Authors: Madhusmita Pradhan; Ranjan Kumar Sahoo, School of Biotechnology, Centurion University of Technology and Management, R.Sitapur-761 211, Odisha, India.
Email: madhusmita.pradhan@cutm.ac.in;
ranjan.sahoo@cutm.ac.in
Orcid id: 0000-0002-9328-3622; 0000-0003-1063-6611

How to cite this article: Palei, M., Mohapatra, M.D., Pradhan, M. and Sahoo, R.K. (2024). Occurrence of Abiotic and Biotic Stress Tolerance in Rice: A Multigene Approach. Indian Journal of Agricultural Research. 58(5): 737-743. doi: 10.18805/IJARe.A-6243.

Submitted: 22-04-2024 **Accepted:** 26-06-2024 **Online:** 17-07-2024

and flood. These varieties will defend against the negative of climate change. The article emphasizes advancements in rice genetics and breeding for stress tolerance, focusing on varieties appropriate for coastal locations where floods and salt are issues and where rising sea levels will limit future rice production.

Abiotic stresses and their action

Drought

Drought is a significant disruptive and hazardous abiotic stress in the current climate change scenario, impacting millions worldwide annually. Drought is determined by rainfall intensity and pattern, lasting from a few days to months or even years. Plants are generally affected by three common drought types: (f) early-season drought, which is responsible for late transplanting and mild intermittent stress. This condition affects the plant's health and is responsible for late-maturing genotypes. Developing drought-resistant rice cultivars is difficult because of the complicated quantitative nature of the variables involved (Ndikuryayo *et al.,* 2023). Healthy plant growth and yielding low water affected the deep root system, with high root length density at depth can help water extraction in highland conditions (Zia *et al*., 2021). Water deficit in drought also inhibits cell expansion, early vegetative stage, internode elongation and decreased plant height, causing a reduction in leaf area. Drought reduces the photosynthetic activity and growth of plants in developmental stages. Severe dryness denatures the photosynthetic proteins (Yang *et al*., 2022). Eastern India developed drought-tolerance rice varieties such as CR dhan, Anjali, Vandana, Indira Barani dhan, Sahbhagi Dhan, Abhishek, Shushk Sanrat, NDR 97 and Susk Samrat (Arora *et al*., 2018). The (IRRI)International Rice Research Institute released and developed several drought-tolerant rice varieties like DRR and Sahbhagi dhan, which are 44, 43 and 42 in India under drought conditions (Kumar *et al*., 2021).

Salinity

Soil salinization is another critical issue that the globe is now confronting. Sodium-induced soil salinity, widely distributed globally, is a leading cause of reduced the production of rice. Salt-affected land area in India amounts for 6.73 million hectares (mha), which is expected to expand to 16.2 million hectares by 2050 (Kundu *et al*., 2022). Among various approaches, marker-assisted breeding has successfully created new, improved and high-yielding rice varieties with enhanced salt tolerance (Rasheed *et al*., 2022). Salt tolerance is a complicated phenomenon that necessitates various independent and interconnected systems. In recent years, developed six salt-tolerance rice lines: CSR56, CSR52, CSR49, CSR76 and CSR60.CSR56, CSR46, CSR76 and CSR60 are long, slender grains tolerant of salinity of EC ~ 8.00 dS/m and sodicity pH of 9.9 (Krishnamurthy *et al*., 2022). Previously, in India, various research was done to get the salt tolerance rice and develop high-yielding indica rice, including IR64, BR11 and BRRI Dhan 28 at the seedling stage (Mare *et al*., 2023). Recent crop research has successfully progressed to using molecular genomics to discover and clone salt-tolerance genes in plant responses to salinity stress (Das *et al*., 2023).

High and low temperature

The earth's surface temperature has increased significantly in recent decades due to global climate changes and rising greenhouse gas emissions. Temperatures are anticipated to climb from 2 to 4 degrees Celsius by 2050 (Xu *et al*., 2021). High-temperature periods last for exceeding eight days, 5-7 days and 3-5 days. They are generally classified as heat injury, moderate and mild. The low temperatures ranging from <0°C and 0 to 15°C are accordingly classed as cold or freezing stress (Yamamoto *et al*., 2012). In the last ten years, Extensive attempts have been undertaken. To identify genes/QTLs that improve cold tolerance in rice and heat are complex traits (Pan *et al*., 2023).

Submergence

One of the most significant obstacles to successful rice production is submergence, which limits the crop's growth and productivity. Notably, over 16% of the global rice-growing regions are susceptible to Flooding. A previous report revealed that Africa and Asia are the most affected continents by flood, which threatens rice cultivation and yield (Koppa *et al*., 2021). Flash floods are a recurrent challenge to rice farming in Southeast Asia's and the South's rainfed lowlands. These floods can result in plants remaining wholly submerged in water for approximately two weeks, negatively impacting rice crop adaptability. However, rice plants can develop anatomic and metabolic traits that enable them to cope with submergence or waterlogging. Aerobic crops cannot withstand waterlogging, whereas paddy may thrive in shallow standing water. The complete submergence of plants caused by impeding growth processes and flash flooding hinders gaseous exchange. This ultimately results in plant mortality and decay (Dar *et al*., 2021). The extent of damage caused by submergence is contingent upon the depth and duration of flood, the topography of the land and floodwater conditions. In 1970, the International Rice Research Institute (IRRI) pioneered identifying submergence- tolerant rice varieties, collecting over 100,000 rice germplasms, including 1,000 submergence-resistant varieties from flood areas.

Heat

Heat stress is a significant abiotic limitation for rice cultivation, following only drought and salinity. High temperatures are prevalent and pose a challenge to rice production. The rise in greenhouse gasses in the atmosphere, resulting in global warming, significantly contributes to the increase in atmospheric temperature. This phenomenon is a significant source of heat stress and negatively impacts rice production (Yang *et al*., 2021). Therefore, identifying heat-tolerant varieties is of utmost importance to ensure stable yields. In this regard, previous

Table 1: Identification of abiotic tolerance gene and their function.

Gene	Source	Function	Phenotypic characteristic of plant	References
OsNAC9	Rice	Enhanced uptake in roots	Tolerance to drought	Jin *et al.*, 2023
OsAR5	Rice	Regulation of stomata closure and chaperon -like protein	Tolerance to drought	Li *et al.*, 2017
OsMYB55	Rice	Modulating expression of drought related genes	Tolerance to drought	Casaretto *et al.*, 2016
OsNAC2	Rice	Reduction of LEA and SAPK expression	Tolerance to drought	Yang *et al.*, 2022
OsSGL	Rice	Increase osmolytes accumulation and root growth	Tolerance to drought	Liu *et al.,* 2022
ZFP177	Rice	tolerance to both low- and high-temperature stresses	Tolerance to high temperature	Huang *et al.,* 2022
nsLTP1	*S. tuberosum*	Regulate expression of stress related gene, Enhance activation of antioxidative defence	Tolerance to heat	Gangadhar *et al.*, 2016
APX	*Pisum sativum*	Ascorbate peroxidese and catalase	Tolerance to heat	Liu *et al.*, 2019
CBF3	*Arabidopsis*	Induce expression of genes involved in photosynthesis activities and antioxidant defence	Tolerance heat	Liang *et al.*, 2022
AVP1	*Arabidopsis*	Tolerated to shortage of water	ToleranceWater deficit	Balasubramaniam *et al.*, 2022
ALDRXV4	*Xerophyta viscosa*	Survived longer period of water deficiency	ToleranceWater deficit	Kumar *et al.*, 2013
OsJRL	Rice	Cell protection and signal transduction	Tolerance to salinity	Gao *et al.*, 2023
OsPEX11	Rice	Regulation in Na^+/K^+ transporter, reduction in ROS accumulation	Tolerance to salinity	Kim *et al.*, 2023
OsVPE3	Rice	Vacuole-mediated PCD, Stomatal development	Tolerance to salinity	Lu *et al.*, 2016
Cat	Wheat	Catalase	Tolerance to cold	Zhang *et al.*, 2022
GS2	Rice	Glutamine synthase	Tolerance to salt and cold	Li *et al.,* 2023
OtsA	*E. coli*	Trehalose biosynthesis	Tolerance to salt, drought and cold	Vanaporn *et al.,* 2020
Spl7	Rice	Heat stress Transcription factor	Tolerance to heat stress	Liu *et al.*, 2022
Pcd,adc	Rice	Pyruvate decarboxylase	Tolerance to submergence	Nakamura *et al.,* 2020

research has identified several rice cultivars that exhibit high heat tolerance, including Indica rice varieties IR36 and IR24, Japonica cultivars such as Koshihikari and Akita Komachi and an aus landrace known as (N22) Nagina 22. Of these, N22 has been found as the highest heat-stress resistant type. Its ability to identify specific chromosomal segments during the reproductive.

Cold

Rice is a cold-sensitive crop subject to abiotic stressors, with low temperatures being the critical limiting factor in its production in temperate and high-elevation regions. The increasing frequency of extreme low-temperature events in recent decades, a consequence of ongoing climate change, has further exacerbated this challenge. As a result, there is a pressing need to develop effective measures to protect rice crops from the harmful effects of these environmental stressors. Such measures could enhance rice production's resilience in the face of climate change, contributing to food security and sustainable development (Yaduvanshi *et al*., 2021). Cold stress is a significant problem that adversely impact on the development and growth of different stages of rice plants including vegetative, reproductive and germination stages, resulting in a considerable decline in yield. At the cold stress, the germination stage negatively impacts the germination speed and the percentage. Various populations have seen numerous quantitative trait loci (QTLs) associated with germinability with low temperatures. reported identifying 11 putative QTLs spread across chromosomes 3, 4, 5, 7, 9, 10 and 11 that regulate low-temperature germinability. However, it is noteworthy that few QTLs were discovered cold tolerance during the bud stages of plant compared to the germination stage of rice (Xu *et al*., 2020).

Types and mechanisms of biotic stresses

Bacterial blight

Bacterial blight (BLB) caused by *Oryzae* (Xoo) *Xanthomonas oryzae* pv. Significantly threatens rice crops. Production losses up to 80-100% in high infection stages

Table 2: Identification of biotic tolerance gene and their function.

Gene	Source	Phenotypic characteristic of plants	References
Cry1AB	*E. coli*	Resistance to insect	Gomez *et al.,* 2023
Cry2A	*Bacillus thuringiensis*	Resistance to insect	Ramalakshmi *et al.,* 2022
Cry2Aa	*Bacillus thuringiensis*	Resistance to insect	Khurshid *et al.,* 2023
Bt and CpT1	Bt bacteria and Liver	Resistance to insect	Xu *et al.,* 2023
Bar	*Streptomyces*	Resistance to herbicide	Li *et al.,* 2023
Bar	*Streptomyces*	Resistance to herbicide	Messeguer *et al.,* 2001
Bar	*Streptomyces*	Resistance to herbicide	Tan *et al.,* 2016
Xa21	Rice	Resistance to bacteria blight	Jiang *et al.,* 2020
Cry1AB/Cry1AC	Bt bacteria	Resistance to YSB	Li *et al.,* 2023
Cry	Bt bacteria	Resistance to YSB	Biswas *et al.,* 2021
Chitinase	Rice	Resistance to fungal infection	Bautista *et al.,* 2022
Bean chitinase	Cotton	Resistance to fungal infection	Navarro-González *et al.,* 2019
Cowpea serin PI	Rice	Resistance to fungal infection	Chiu *et al.,* 2022

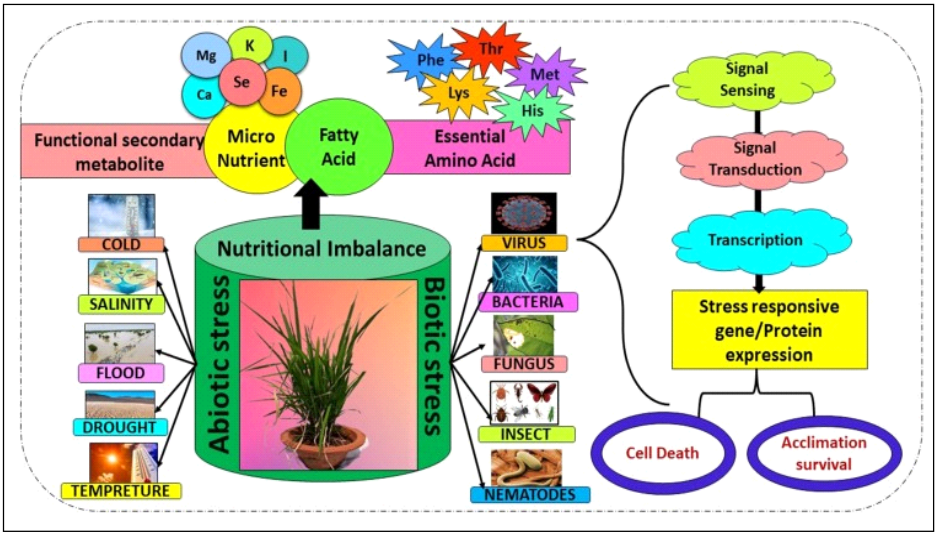

Fig 1: Environmental stress responding to rice plant: Biotic and abiotic stress types and their action towards the plant.

have been reported, with moderate infections leading to a loss of 20-30% (Yang *et al*., 2022). These losses are attributed to some part of seed grain filling those results from very low photosynthetic action. Only 11 of the 45 resistant (R) genes found by BLB were fine-mapped and cloned for use in contemporary biotechnology. A marker-assisted pyramiding strategy combined four BLB-resistant genes (Xa5, Xa21, xa4 and xa13) of high-yielding rice varieties, resulting in broader and more permanent resistance. This approach has resulted in the most stable combination of BB genes, displaying resistance to most pathogen isolates (Kumar *et al*., 2023). BB R genes identified as wild, domesticated species landraces and mutants that are resistant against different Xoo strains.

Blast

The fungus *Pyricularia oryzae* is a potent threat to rice production, a staple crop that sustains millions worldwide. Rice blast, caused by this fungus, presents significant challenges to rice cultivation. This disease poses a substantial risk to global food security and has the potential to cause significant economic damage (Devanna *et al*., 2022). As such, it is critical to develop strategies to mitigate the impact of *Pyricularia oryzae* and prevent its spread over a hundred blast-resistant genes have been discovered, with barely thirty cloned and functionally described.

Brown plant hopper

The brown plant hopper (BPH), scientifically known as *Nilaparvata lugens*, is a well-known and highly destructive insect pest that inflicts significant damage on rice crops across Asia. The impact of BPH infestations on rice crops is profound, causing losses of up to 60% of the total yield. This insect pest has become a significant concern for farmers and agricultural researchers, continuously seeking effective strategies to mitigate its impact on rice production. Identifying and functionalizing genes that confer resistance to brown planthoppers (BPH) provides a unique chance to use genes in marker-assisted gene introgression programs efficiently.

Around 40 BPH resistance genes have been found, of which 17 have been extracted and cloned using a map-based method. Recently, genes known to confer 70 BPH resistance identified. Of the 50 genes and 20 QTLs, identified genes and quantitative trait loci (QTLs) were found to be equally derived from wild rice, while only 35 resistance genes/QTLs were sourced from *Oryza sativa*. This knowledge is crucial for comprehending their evolution and, ultimately, for developing efficacious strategies for their management and control (Ishwarya *et al*., 2022).

Gall midge

The Asian rice (*Orseolia oryzae*) gall midge is an insect pest rice that is commonly found in Southeast Asia, China and India during the wet season. The goal was to improve the resistance of these cultivars to the gall midge bug, a significant pest in rice production. This was achieved through the use of marker-assisted introgression/ pyramiding techniques. The study results indicate that incorporating these genes significantly improved the resistance of the cultivars to the gall midge insect. This approach presents a viable and promising strategy for developing rice cultivars with improved pest resistance, which is critical for ensuring the sustainability of rice production. Through this approach, advancements in rice breeding can be made towards creating cultivars with improved resistance to pests, thereby reducing the need for chemical pesticides and ultimately leading to healthier and more sustainable rice crops. The successful integration of these genes will contribute towards developing disease-resistant rice cultivars and provide a sustainable solution to the problem of gall midge infestation in rice production.

CONCLUSION

It is expected that climate change will impact rice production in tropical Asia. The detrimental effects can be attributed to direct temperature increases and challenges arising from extreme weather events and rising sea levels. These challenges include drought, submergence and salinity. The increasing salinity and flooding are predicted to pose serious problems for the delta and coastal areas. An efficient method for improving rice crop resistance to bacterial blight, gall midge, blast and salinity tolerance is marker-assisted multigene pyramiding.

ACKNOWLEDGEMENT

The author thanks Centurion University of Technology and Management, Bhubaneswar, Odisha, India, for the invaluable support in completing this manuscript.

Conflict of interest

The authors declare no conflict of interest.

REFERENCES

Arora, A., Bansal, S. and Ward, P. (2018). Do farmers value rice varieties tolerant to droughts and floods? Evidence from a discrete choice experiment in Odisha, India. Water Resources and Economics. 25: 27-41.

Bairagi, S., Bhandari, H., Das, S.K. and Mohanty, S. (2021). Flood-tolerant rice improves climate resilience, profitability and household consumption in Bangladesh. Food Policy. 105: 0306-9192.

Balasubramaniam, T., Wijewardene, I., Hu, H., Shen, G., Zhang, J. and Hong-Zhang, H. (2022). Co-overexpression of AVP1, PP2A-C5 and AtCLCc in Arabidopsis thaliana greatly increases tolerance to salt and drought stresses. Environmental and Experimental Botany. 200: 104934.

Bautista, J.A.L., Bautista-Baños, S., Ventura-Aguilar, R.I., Hernández-López, M. (2022). Chitinases in plants and possible use as biomarkers for the design of biosensors in the detection of phytopathogenic fungi. Revista Mexicana Ciencias Agricolas. 13(4): 701-713.

Biswas, P.L., Nath, U.K., Ghosal, S., Goswami, G., Uddin, M.S., Ali, O.M., Latef, A.A.H.A., Laing, A.M., Gao, Y.M. and Hossain, A. (2021). Introgression of bacterial blight resistance genes in the Rice cultivar ciherang: Response against *Xanthomonas oryzae* pv. *oryzae* in the F_6 generation. Plants (Basel). 10(10): 2048.

Casaretto, J.A., El-kereamy, A., Zeng, B., Stiegelmeyer, S.M., Chen, X., Bi, Y.M. and Rothstein, S.J. (2016). Expression of OsMYB55 in maize activates stress-responsive genes and enhances heat and drought tolerance. BMC Genomics. 29(17): 312.

Chiu, T., Poucet, T. and Li, Y. (2022). The potential of plant proteins as antifungal agents for agricultural applications. Synthetic and Systems Biotechnology. 7(4): 1075-1083.

Dar, M.H., Bano, D.A., Waza, S.A., Zaidi, N.W., Majid, A., Shikari, A.B., Ahangar, M.A., Hossain, M., Kumar, A. and Singh, U.S. (2021). Abiotic stress tolerance-progress and pathways of sustainable rice production. Sustainability. 13: 2078.

Das Mohapatra, M., Poosapati, S., Sahoo, R.K. and Swain, D.M. (2023). Helicase: A genetic tool for providing stress tolerance in plants. Plant Stress. 9: 100171-100181.

Devanna, B.N., Jain, P., Solanke, A.U., Das, A., *et al*. (2022). Understanding the dynamics of blast resistance in Rice-*magnaporthe oryzae* interactions. Journal of Fungi. 8(6): 584.

Gangadhar, B.H., Sajeesh. K., Venkatesh, J., Baskar, V., Kumar, A., Yu, J.W., Prasad and R., Mishra, R. (2016). Enhanced tolerance of transgenic potato plants over-expressing non-specific lipid transfer Protein-1(StnsLTP1) against multiple abiotic stresses. Frontiers in Plant Science. 22(7): 1228.

Gao, Q., Yin, X., Wang, F., Zhang, C., Xiao, F., Wang, H., Hu, S., Liu, W., Zhou, S., Chen, L., Dai, X. and Liang, M. (2023). Jacalin-related lectin 45 (OsJRL45) isolated from 'sea rice 86' enhances rice salt tolerance at the seedling and reproductive stages. BMC Plant Biology. 23: 553.

Gomez, B.I.G., Sánchez, T.A., Cano, S.N., Nascimento, N.A., Bravo, A. and Soberón, M. (2023). Insect chaperones Hsp70 and Hsp90 cooperatively enhance toxicity of *Bacillus thuringiensis* Cry1A toxins and counteract insect resistance. Frontiers Immunology. 14: 1151943.

Huang, Y., Du, L., Wang, M., Ren, M., Yu, S. and Yang, Q. (2022). Multifaceted roles of zinc finger proteins in regulating various agronomic traits in rice. Frontiers in Plant Science. 13: 974396.

Ishwarya Lakshmi, V.G., Sreedhar, M., Jhansi Lakshmi, V., Gireesh, C., Rathod, S., Bohar, R., Deshpande, S., Laavanya, R., Kiranmayee, K.N.S.U., Siddi, S. and Vanisri, S. (2022). Development and validation of diagnostic KASP markers for brown planthopper resistance in rice. Frontiers in Genetics. 3: 914131.

Jiang, N., Yan, J. and Liang, Y. (2020). Resistance genes and their interactions with bacterial blight/leaf streak pathogens (*Xanthomonas oryzae*) in rice (*Oryza sativa* L.) an Updated Review. Rice. 13: 3.

Jin, X., Zheng, Y., Wang, J., Chen, W., Yang, Z., Chen, Y., Yang, Y., Lu, G. and Sun, B. (2023). SbNAC9 Improves drought tolerance by enhancing scavenging ability of reactive oxygen species and activating stress-responsive genes of sorghum. International Journal of Molecular Science. 24(3): 2401.

Khurshid, H., Zaheer, H., Yunus, FuN., Manzoor, F., Latif, A.A. and Rashid, F. (2023). Site-directed mutagenesis in Cry proteins of *Bacillus thuringiensis* to demonstrate the role of domain II and domain III in toxicity enhancement toward *Spodoptera litura*. Egyptian Journal of Biological Pest Control. 33: 86.

Kim, J.H., Lim, S.D., Jung, K.H. and Jang, C.S. (2023). Overexpression of a C3HC4-type RING E3 ligase gene, OsRFPHC-13, Improves salinity resistance in rice, *Oryza sativa*, by altering the expression of Na+/K+ transporter genes. Environmental and Experimental Botany. 207: 105224.

Koppa, N. and Amarnath, G. (2021). Geospatial assessment of flood-tolerant rice varieties to guide climate adaptation strategies in India. Climate. 9(10): 151.

Krishnamurthy, S.L., Lokeshkumar, B.M., Rathor, S., Warraich, A.S., Yadav, S., Gautam, R.K., Singh, R.K. and Sharma, P.C. (2022). Development of Salt-tolerant Rice Varieties to Enhancing Productivity in Salt-affected Environments. Environmental Sciences Proceedings. 16(1): 30.

Kumar, A., Raman, Yadav, S., Verulkar, S.B., *et al.* (2021). Genetic gain for rice yield in rainfed environments in India. Field Crops Research. 260: 107977.

Kumar, D., Singh, P., Yusuf, M.A., Upadhyaya, C.P., Roy, S.D., Hohn, T. and Sarin, N.B. 2013. The *Xerophyta viscosa* aldose reductase (ALDRXV4) confers enhanced drought and salinity tolerance to transgenic tobacco plants by scavenging methylglyoxal and reducing the membrane damage. Molecular Biotechnology. 4(2): 292-303.

Kumar, S. and Khanna, M. (2023). Distributional heterogeneity in climate change impacts and adaptation: Evidence from Indian agriculture. Agricultural Economics. 54: 147-160.

Kundu, S., Perinjelil, S.J. and Thakur, N. (2022). Soil salinization and bioremediation using halophiles and halotolerant microorganisms. Academic Press. 11: 231-256.

Li, C., Wang, J., Ling, F. and You, A. (2023). Application and development of *Bt* insect resistance genes in rice breeding. Sustainability. 15: 9779.

Li, J., Li, Y., Yin, Z., Jiang, J., Zhang, M., Guo, X., *et al*. (2017). OsASR5 enhances drought tolerance through a stomatal closure pathway associated with ABA and H_2 O_2 signalling in rice. Plant Biotechnology Journal. 15(2): 183-196.

Li, Z., Zhang, Z., Liu, Y., Ma, Y., Lv, X., Zhang, D., *et al*. (2023). Identification and expression analysis of EPSPS and BAR families in cotton. Plants. 12: 3366.

Li, Z., Zhu, M., Huang, J., Jiang, S., Xu, S., Zhang, Z., He, W. and Huang, W. (2023). Genome-wide comprehensive analysis of the nitrogen metabolism toolbox reveals its evolution and abiotic stress responsiveness in rice (*Oryza sativa* L.). International Journal of Molecular Sciences. 24(1): 288.

Liang, L., Tang, W., Lian, H., Sun, B., Huang, Z., Sun, G., Li, X., Tu, L., Li, H. and Tang, Y. (2022). Grafting promoted antioxidant capacity and carbon and nitrogen metabolism of bitter gourd seedlings under heat stress. Frontiers of Plant Science. 13: 1074889.

Liu, J.X., Feng, K., Duan, A.Q., Li, H., Yang, Q.Q., Xu, Z.S. and Xiong, A.S. (2019). Isolation, purification and characterization of an ascorbate peroxidase from celery and overexpression of the AgAPX1 gene enhanced ascorbate content and drought tolerance in Arabidopsis. BMC Plant Biology. 19(1): 488.

Liu, K., Minjuan, L., Zhang, B., Xuming, Y., Xinjie, X., Manling, W. and Yanchun, C. (2022). Poaceae Orthologs of Rice OsSGL, DUF1645 Domain-containing genes, positively regulate drought tolerance, grain length and weight in rice. Rice Science. 29: 3.257-267.

Lu, W., Deng, M., Guo, F., Wang, M., Zeng, Z., Han, N., Yang, Y., Zhu, M. and Bian, H. (2016). Suppression of OsVPE3 enhances salt tolerance by attenuating vacuole rupture during programmed cell death and affects stomata development in rice. Rice. 29(9): 65. doi: 10.1186/s12284-016-0138-x.

Mare, C., Zampieri, E., Cavallaro, V., Frouin, J., Grenier, C., *et al.* (2023). Marker-assisted introgression of the salinity tolerance locus saltol in temperate japonica rice. Rice. 16(1): 2. doi: 10.1186/s12284-023-00619-2.

Messeguer, J., Fogher, C. and Guiderdoni, E. (2001). Field assessments of gene flow from transgenic to cultivated rice (*Oryza sativa* L.) using a herbicide resistance gene as tracer marker. Theoretical and Applied Genetics. 103: 1151-1159.

Nakamura, M. and Noguchi, K. (2020). Tolerant mechanisms to O_2 deficiency under submergence conditions in plants. Journal of Plant Research. 133(3): 343-371.

Navarro-González, S.S., Ramírez-Trujillo, J.A., Peña-Chora, G., Gaytán, P., Roldán-Salgado, A., *et al.* (2019). Enhanced tolerance against a fungal pathogen and insect resistance in transgenic tobacco plants overexpressing an endochitinase gene from *Serratia marcescens*. International Journal of Molecular Science. 20(14): 3482.

Ndikuryayo, C., Ndayiragije, A., Kilasi, N.L. and Kusolwa, P. (2023). Identification of drought tolerant rice (*Oryza Sativa* L.) Genotypes with asian and african backgrounds. Plants (Basel). 12(4): 922.

Pan, Y.H., Nong, B.X., Chen, L., Yang, X.H., Xia, X.Z., Zhang, Z.Q., Qing, D.J., Gao, J., Huang, C.C., Li, D.T. and Deng, G.F. (2023). QTL mapping and identification of candidate genes for cold tolerance at the germination stage in wild rice. Genes Genomics. 45(7): 867-885.

Ramalakshmi, A., Udayasuriyan, V. and Balasubramani, V. (2022). Molecular cloning of a new cry2A-type gene from *Bacillus thuringiensis* strain Nn10 and its expression studies. Microbial Pathogenesis. 164: 105415.

Rasheed, A., Li, H., Nawaz, M., Mahmood, A., Hassan, M.U. *et al.* (2022). Molecular tools, potential frontiers for enhancing salinity tolerance in rice: A critical review and future prospective. Frontiers in Plant Science. 13: 966749.

Sahoo, R.K. and Pradhan, M. (2014). *Azotobacter vinellandii* SINAz1 increases growth and productivity in rice under salinity stress. Legume Research. 46(2): 196-203. doi: 10.18805/LR-4335.

Tan, L., Chan, K., Lee, L. and Goh, B. (2016). *Streptomyces* bacteria as potential probiotics in aquaculture. Frontiers in Microbiology. 7. https://doi.org/10.3389/fmicb.2016.00079.

Vanaporn, M. and Titball, R.W. (2020). Trehalose and bacterial virulence. Virulence. 11(1): 1192-1202. doi: 10.1080/21505594.2020.1809326.

Xu, T., Wang, Y., Wang, Y., Bi, S., Hu, B., Hu, F. and Xu, L. (2023). Comparison of gut microbial community between Bt-Resistant and susceptible strains of *Ostrinia furnacalis*. Agronomy. 13: 1923.

Xu, Y., Chu, C. and Yao, S. (2021). The impact of high-temperature stress on rice: Challenges and solutions. The Crop Journal. 9(5): 963-976.

Xu, Y., Wang, R., Wang, Y., Zhang, L. and Yao, S. (2020). A point mutation in LTT1 enhances cold tolerance at the booting stage in rice. Plant, Cell and Environment. 43(4): 992-1007.

Yaduvanshi, A., Nkemelang, T., Bendapudi, R. and New, M. (2021). Temperature and rainfall extremes change under current and future global warming levels across Indian climate zones. Weather and Climate Extremes. 31: 100291.

Yamamoto, T., Fujita, M., Oda, Y., Todani, M., Hifumi, T., Kondo, Y. *et al.* (2018). Evaluation of a novel classification of heat-related illnesses: a multicentre observational study (Heat Stroke STUDY 2012). International Journal of Environmental Research and Public Health. 15(9): 1962.

Yang, X., Lu, M., Wang, Y., Wang, Y., Liu, Z. and Chen, S. (2021). Response mechanism of plants to drought stress. Horticulturae. 7: 50.

Yang, Y., Yu, J., Qian, Q. and Shang, L. (2022). Enhancement of heat and drought stress tolerance in rice by genetic manipulation: A systematic review. Rice (N Y). 15(1): 67.

Zhang, Y., Zheng, L., Yun, L., Ji, L., Li, G., Ji, M., Shi, Y. and Zheng, X. (2022). Catalase (CAT)gene family in wheat (*Triticum aestivum* L.) evolution, expression pattern and function analysis. International Journal of Molecular Science. 23(1): 542.

Zia, R., Nawaz, M.S., Siddique, M.J., Hakim, S. and Imran, A. (2021). Plant survival under drought stress: Implications, adaptive responses and integrated rhizosphere management strategy for stress mitigation. Microbiology. 242: 126626.