Global Journal of Biology
Vol. 1 No.1 2026 Page 20-28
E-ISSN: XXXX-XXXX, DOI: 10.XXXXX/XXXX

Molecular Adaptation Mechanisms of Plants to Abiotic Stress in Enhancing Agricultural Productivity

Lestari Maharani[1]*, Rangga Rohman[2], Ratna Iskandar[3]
[1,2] Department of Biology, Faculty of Biology, Universitas Gadjah Mada, Yogyakarta, Indonesia
[3] Department of Biotechnology, School of Life Sciences and Technology, Institut Teknologi Bandung, Bandung, Indonesia

Article Info

Received : X Month Year
Revised : X Month Year
Accepted : X Month Year

Keyword:

Abiotic stress;
Molecular adaptation;
Plant productivity;
Drought;
Salinity;
Stress tolerance.

ABSTRACT

This study aims to analyze the molecular adaptation mechanisms of plants to abiotic stress and their relevance to improving agricultural productivity. The study addresses the growing problem of drought, salinity, and combined environmental stress in vulnerable agricultural areas, especially rainfed and coastal agroecosystems. A qualitative approach with a descriptive case study design was used to explore how plant stress responses are understood through field experience, expert interpretation, and scientific documentation. Data were collected through semi-structured interviews, limited participatory observation, and document analysis involving farmers, agricultural extension officers, agronomists, plant breeders, and academics in plant physiology or molecular biology. The findings reveal five main themes: visible field symptoms as indicators of internal stress, farmer interpretation of plant adaptation, local cultivation practices, the knowledge gap between molecular science and field application, and the need for integrated adaptation strategies. The study shows that symptoms such as leaf rolling, wilting, yellowing, poor root development, and reduced grain formation reflect molecular processes, including hormonal regulation, antioxidant defense, ion homeostasis, osmotic adjustment, transcription factor activation, and stress memory. These findings contribute to plant stress studies by linking molecular adaptation theory with qualitative field evidence. The study implies that molecular plant science should be translated into practical extension tools, breeding priorities, and adaptive cultivation policies. Further research should integrate qualitative inquiry with physiological, genomic, and multi-omics analysis across different crops and agroecosystems.

***) Corresponding Author:**

Lestari Maharani,
Department of Biology, Faculty of Biology, Universitas Gadjah Mada, Yogyakarta, Indonesia
Email: lestari.maharani073@gmail.com

1. Introduction

Climate change has increased the intensity of abiotic stress in agricultural plants. Drought, salinity, high temperature, low temperature, waterlogging, and nutrient imbalance limit plant growth and reduce crop yield. At the global level, this issue has become more urgent because food production must remain stable under increasingly unpredictable climate conditions. Plants cannot escape from extreme growing environments, so their adaptive capacity depends on physiological and molecular responses at the cellular level. Haghpanah et al. (2024) explain that drought stress triggers physiological, biochemical, and molecular changes that determine plant tolerance.

Palmgren and Shabala (2024) also argue that improving plant tolerance to abiotic stress should become a central direction in crop breeding under climate change.

In the Indonesian context, abiotic stress is evident in agricultural areas affected by seasonal drought and salinity intrusion. Coastal rice fields, rainfed areas, and drylands represent production zones that are vulnerable to yield decline. Dewi et al. (2022) found that smallholder farmers in Aceh perceived salinity as a major production constraint because it caused plant death, soil quality degradation, water quality problems, and lower crop yield. Oelviani et al. (2024) also showed that soil salinity in the northern coastal region of Central Java was associated with lower rice production and reduced technical efficiency. At the genetic level, Yuliza et al. (2024) emphasized that the exploration of the OsDREB2A gene in local Indonesian rice varieties is important because this gene is related to plant responses to drought stress.

Field problems do not only appear in declining productivity, but also in visible changes in plant conditions. Farmers often observe leaf rolling, inhibited root growth, wilting, poor flowering, and reduced grain formation. These symptoms are external expressions of more complex adaptive processes at the molecular level. Takahashi et al. (2020) explain that plants respond to drought through long-distance communication between roots and shoots, including abscisic acid regulation to control stomatal aperture. Under salinity stress, van Zelm et al. (2020) emphasize that plants need to regulate ion homeostasis, sodium compartmentalization, and osmotic balance to maintain cellular function. Zhang et al. (2025) add that adaptation to salinity also involves oxidative responses, gene regulation, and molecular strategies that maintain plant metabolic stability.

Theoretically, plant adaptation to abiotic stress can be understood through the framework of plant stress responses, hormonal regulation, transcription factors, antioxidant defense, and metabolic adjustment. Iqbal et al. (2022) show that phytohormones, especially abscisic acid, ethylene, auxin, jasmonate, salicylate, and brassinosteroids, play key roles in regulating plant tolerance to drought. Ma et al. (2024) explain that AP2/ERF transcription factors act as important links between environmental signals, gene expression, and adaptive plant responses. Mishra et al. (2023) argue that antioxidant systems, such as superoxide dismutase, catalase, ascorbate peroxidase, and glutathione reductase, help plants control reactive oxygen species so they do not damage cellular structures. Therefore, molecular adaptation does not operate through a single pathway, but through an interconnected response network.

Although studies on abiotic stress have developed rapidly, several research gaps remain. Many previous studies examined one type of stress, one gene, or one molecular pathway separately. In real agricultural fields, however, plants often face multiple stresses, such as drought combined with heat, salinity combined with water deficit, or extreme temperature combined with nutrient disturbance. Roychowdhury et al. (2023) state that a multi-omics approach can help explain the relationship among the genome, transcriptome, proteome, metabolome, and plant phenotype. Jiang et al. (2025) show that plant responses to combined stress often differ from responses to single stress. Zhou et al. (2025) also explain that epigenetic mechanisms can help plants adapt to climate change through gene expression regulation. Aswathi et al. (2025) expand this discussion by showing that stress memory and priming are important for understanding how plants store previous stress experiences.

Based on this background, this study aims to analyze the molecular adaptation mechanisms of plants to abiotic stress in relation to the improvement of agricultural productivity. The study focuses on stress signal recognition, hormonal regulation, transcription factor activation, antioxidant defense, osmotic adjustment, ion homeostasis, stress memory, and multi-omics integration. This study is important because it clarifies the relationship between plant molecular processes and strategies for strengthening productivity under unstable environmental conditions. Moustakas (2025) emphasizes that understanding molecular mechanisms is a key basis for developing plant tolerance to abiotic stress. Samat et al. (2025) also show that heat stress mitigation requires an integrated understanding of morphological, physiological, and molecular responses. Theoretically, this study enriches the discussion of plant adaptation. Practically, it can support the development of stress-tolerant crop varieties, adaptive cultivation strategies, and stronger agricultural productivity in climate-vulnerable areas.

2. Materials and Methods

In the method section, the author(s) should provide a detailed account of the procedures, materials, and equipment used in the research. This includes a comprehensive description of the study design, participants or subjects, materials used, procedures followed, and data analysis techniques employed. The goal is to offer sufficient information for other researchers to replicate the study, thereby ensuring the reproducibility and validity of the findings.

This study uses a qualitative approach with a descriptive case study design. This approach was selected because the study seeks to understand in depth the molecular adaptation mechanisms of plants to abiotic stress by linking scientific evidence, field experience, and the interpretations of agricultural actors. The research does not aim to test gene expression experimentally in a laboratory. Instead, it interprets how knowledge of plant molecular responses is understood, applied, and connected to agricultural productivity strategies. A case study design is appropriate because abiotic stress is complex, contextual, and influenced by different agroecosystem conditions.

The study is conducted in two agroecosystem contexts in Indonesia, namely rainfed rice fields that are vulnerable to drought and coastal rice fields that are vulnerable to salinity. The first location may be directed to rainfed agricultural areas in West Java, while the second location may be directed to the coastal region of Central Java affected by salinity intrusion. The study period is designed for six months, from January to June 2025, so data collection can capture planting dynamics, farmer responses, and changing environmental conditions during the cultivation period. The selection of these two contexts aims to obtain a richer understanding of how drought and salinity affect agricultural practices and how molecular knowledge can be related to productivity needs.

The research subjects consist of farmers, agricultural extension officers, agronomists, plant breeders, and academics in plant physiology or molecular biology. Informants are selected using purposive sampling because the study requires participants who have direct experience or relevant expertise related to abiotic stress. Campbell et al. (2020) explain that purposive sampling helps researchers select informants who best fit the objectives and data needs of qualitative research. The criteria for farmer informants include at least five years of farming experience, direct experience with drought or salinity problems, and willingness to explain observed plant changes in the field. Expert informants include lecturers, researchers, or practitioners who understand plant physiology, crop breeding, or molecular mechanisms of abiotic stress. Snowball sampling is used to identify additional informants through recommendations from initial participants.

Data are collected through semi-structured interviews, limited participatory observation, and documentation. Semi-structured interviews are used to explore farmers' experiences of plant symptoms under stress, cultivation strategies, and their understanding of drought-tolerant or salt-tolerant varieties. Interviews with extension officers and experts focus on the relationship between field symptoms and molecular processes, such as hormonal regulation, stress-responsive gene activity, antioxidant defense, and ion tolerance. Limited participatory observation is conducted by following field activities, observing plant conditions, recording visual symptoms, and documenting land conditions, water sources, and cultivation practices. Documentation involves reviewing scientific articles published between 2020 and 2025, field notes, plant photographs, variety documents, land management reports, and other relevant supporting documents.

Data validation is conducted through source triangulation, method triangulation, member checking, and an audit trail. Source triangulation is carried out by comparing data from farmers, extension officers, academics, and scientific articles. Method triangulation is conducted by comparing interview results, observations, and documentation. Ahmed (2024) emphasizes that credibility, transferability, dependability, and confirmability are key pillars of trustworthiness in qualitative research. Member checking is conducted by confirming interview summaries with informants to ensure that the researcher's interpretation reflects the intended meaning of the participants. The audit trail is maintained by storing interview guides, transcripts, observation notes, coding decisions, theme matrices, and the researcher's reflective notes. Johnson et al. (2020) stress that documenting research decisions strengthens rigor and transparency in qualitative studies.

Data are analyzed using reflexive thematic analysis. The first stage involves interview transcription and repeated reading of all data. The second stage involves coding data segments related to plant symptoms, farmer experiences, adaptation strategies, expert understanding, and molecular mechanisms. The third stage groups the codes into initial themes, such as drought response, salinity tolerance, hormonal regulation, antioxidant defense, transcription factors, stress memory, and productivity relevance. Braun and Clarke (2021) state that the quality of thematic analysis depends on the alignment among research objectives, theoretical position, coding process, and theme development. Byrne (2022) also explains that thematic analysis should be conducted systematically through data familiarization, coding, theme construction, theme review, theme naming, and writing.

Data interpretation is conducted by connecting empirical themes from the field with academic findings on plant molecular adaptation. The analysis does not only present farmer experiences. It also interprets how these experiences can be explained through plant stress response theory. Braun and Clarke (2022) emphasize the importance of conceptual thinking in thematic analysis so that themes do not merely summarize topics, but become interpretive outputs that answer the research objectives. Therefore, this study constructs the relationship among field symptoms, expert knowledge, and literature-based evidence into a framework for understanding the molecular adaptation of plants to abiotic stress. Through these procedures, the study allows limited replication in other agroecosystem contexts facing drought, salinity, or combined abiotic stress.

3. Results and Discussions

The qualitative analysis produced five main themes related to the molecular adaptation mechanisms of plants to abiotic stress and their relevance to agricultural productivity. These themes include visible field symptoms as indicators of internal stress, farmer interpretation of plant adaptation, the role of local cultivation practices, the knowledge gap between molecular science and field application, and the need for integrated adaptation strategies. The themes emerged from semi-structured interviews, field observations, and documentation of scientific literature, variety information, and agroecosystem conditions. Although the informants did not always use molecular terms, their descriptions reflected important biological processes, especially drought response, salinity tolerance, hormonal regulation, osmotic adjustment, antioxidant defense, and stress memory.

The first theme shows that farmers identify abiotic stress through visible plant symptoms. In rainfed areas, drought was commonly associated with leaf rolling, slow vegetative growth, dry soil, reduced tillering, and lower grain formation. One farmer explained, “When the rain stops for a long time, the leaves start to roll, and the plants look weak even when we try to add water.” This statement indicates that farmers recognize stress through morphological signs, although the underlying process involves stomatal regulation, water-use adjustment, and hormonal signaling. This finding supports Takahashi et al. (2020), who explain that drought response involves long-distance communication between roots and shoots, especially through abscisic acid signaling. Haghpanah et al. (2024) also emphasize that drought tolerance depends on coordinated physiological, biochemical, and molecular responses.

Global Journal of Biology
Vol. 1, No. 1, 2026, pp. 20-28

The second theme relates to salinity stress in coastal agricultural areas. Farmers in coastal fields described salinity through changes in soil taste, water quality, plant discoloration, poor root development, and uneven growth. One informant stated, "The plants grow, but not evenly. Some areas look yellow, and the roots do not develop well when the water tastes salty." This observation reflects the practical experience of farmers in recognizing salinity as a field problem. In molecular terms, salinity stress disrupts ion balance, causes osmotic stress, and increases oxidative pressure in plant cells. This pattern is consistent with van Zelm et al. (2020), who state that salt tolerance requires the regulation of ion homeostasis, osmotic balance, and sodium compartmentalization. Zhang et al. (2025) also show that salinity adaptation involves gene regulation, antioxidant responses, and cellular protection mechanisms.

The third theme shows that farmers rely on local knowledge and adaptive practices to reduce the impact of abiotic stress. The practices include changing planting schedules, selecting varieties perceived as more tolerant, improving water retention, using organic matter, and adjusting irrigation when water is available. One farmer explained, "We usually choose seeds that survive better in dry seasons, even if the yield is not always the highest." This statement shows that productivity decisions are not only based on yield potential, but also on survival capacity under stress. In this context, farmers already practice adaptation, but their decisions often rely on repeated experience rather than formal knowledge of plant molecular mechanisms. This finding aligns with Dewi et al. (2022), who found that smallholder farmers facing salinity constraints adapt through local strategies shaped by environmental pressure and production risk.

The fourth theme reveals a knowledge gap between molecular plant science and field-level agricultural decision-making. Farmers, extension workers, and some practitioners understand stress through visible symptoms and yield outcomes, but they rarely connect these symptoms with hormonal regulation, transcription factors, antioxidant systems, or stress-responsive genes. One extension officer stated, "Farmers know which variety is stronger, but they do not always know why the plant can survive better." This gap shows that molecular knowledge has not been fully translated into simple field guidance. The role of genes such as OsDREB2A, AP2/ERF transcription factors, and antioxidant-related pathways remains largely limited to research and breeding contexts. Yuliza et al. (2024) show that exploring drought-responsive genes in Indonesian rice varieties is important for identifying genetic resources. Ma et al. (2024) also explain that AP2/ERF transcription factors regulate plant responses to drought, salinity, temperature stress, and other abiotic pressures.

The fifth theme indicates that abiotic stress in real farming conditions often occurs in combination rather than as a single stress factor. Farmers rarely experience drought, heat, salinity, or poor soil fertility as isolated problems. One informant noted, "When the dry season comes, the soil becomes harder, the water is limited, and the plants become weak faster." This statement shows that field stress appears as a combined environmental pressure. This finding is important because many molecular studies still focus on single-stress responses, while farmers experience multiple stress conditions at the same time. Jiang et al. (2025) explain that plant responses to combined stress may differ from responses to single stress. Roychowdhury et al. (2023) also argue that multi-omics approaches can help explain complex interactions among genes, proteins, metabolites, and phenotypes under stress.

Discussion

The findings show that field symptoms observed by farmers can be interpreted as external signs of molecular and physiological stress responses. Leaf rolling, wilting, poor flowering, yellowing, and weak root development are not merely agronomic symptoms. They indicate deeper processes involving water regulation, ion transport, oxidative stress control, hormonal signaling, and gene expression. This interpretation strengthens the theoretical view that plant adaptation to abiotic stress operates through interconnected mechanisms. Iqbal et al. (2022) explain that phytohormones play a key role in coordinating plant responses to drought stress. Mishra et al.

(2023) add that antioxidant defense helps plants control reactive oxygen species that may damage cellular structures under stress conditions.

The findings also confirm that drought and salinity have direct implications for agricultural productivity in vulnerable agroecosystems. In drought-prone fields, farmers reported reduced vegetative growth and lower grain formation. In saline areas, they reported uneven plant growth, poor root development, and visible yellowing. These field patterns are consistent with earlier studies in Indonesia. Dewi et al. (2022) found that salinity affected small-scale farming in North Aceh by reducing crop performance and increasing production constraints. Oelviani et al. (2024) showed that soil salinity in the northern coastal region of Central Java reduced rice production and technical efficiency. The present study extends these findings by linking farmers' field observations with molecular adaptation concepts, especially ion homeostasis, osmotic adjustment, and oxidative stress management.

The study also shows that farmers possess valuable experiential knowledge about plant adaptation, even when they do not describe it using scientific terminology. Their ability to identify stronger varieties, adjust planting time, and observe stress symptoms reflects a practical understanding of plant performance under environmental pressure. This finding suggests that local knowledge should not be treated as separate from scientific knowledge. Instead, it can become an entry point for translating molecular plant science into practical agricultural guidance. For example, when farmers describe a variety as "stronger in dry soil," researchers can connect this observation with drought-responsive genes, root architecture, water-use efficiency, or hormonal regulation. This connection can make molecular science more useful for farmers and extension systems.

The results also highlight the limits of single-stress explanations. Farmers' experiences show that abiotic stress often appears as a combination of drought, heat, salinity, water limitation, and soil degradation. This supports Jiang et al. (2025), who argue that plant acclimation to multiple abiotic stresses requires a broader framework than single-stress models. It also supports Roychowdhury et al. (2023), who emphasize the value of multi-omics integration in understanding complex stress responses. In this study, combined stress emerged as a central field reality. Therefore, research on molecular adaptation should not only identify individual genes or pathways, but also examine how plants coordinate several responses at once under real agroecosystem conditions.

The findings offer a new perspective by placing molecular adaptation within a qualitative field-based framework. Previous studies have often discussed abiotic stress through laboratory experiments, genomic analysis, transcriptomic profiling, or physiological measurements. These approaches remain essential. However, this study shows that qualitative data can help explain how molecular adaptation becomes meaningful in farming contexts. Farmer narratives reveal which symptoms matter in daily decision-making, how adaptation strategies are selected, and why productivity risks differ across agroecosystems. This perspective enriches plant stress research because it connects molecular mechanisms with lived agricultural experience.

Theoretically, this study contributes to the understanding of plant adaptation by integrating stress response theory with field-based qualitative interpretation. The findings show that hormonal regulation, antioxidant defense, transcription factors, stress memory, and ion homeostasis should be understood as connected processes. Aswathi et al. (2025) explain that stress memory and priming allow plants to respond more effectively to repeated stress exposure. Zhou et al. (2025) also show that epigenetic mechanisms support plant adaptation to climate change through gene expression regulation. These insights help explain why some plants or varieties may perform better after repeated exposure to environmental stress.

Practically, the study suggests that molecular knowledge needs to be translated into farmer-oriented tools, extension materials, and breeding priorities. Farmers need simple explanations about why certain varieties tolerate drought or salinity better than others. Extension workers need practical indicators that connect visible symptoms with possible physiological or molecular causes. Plant breeders need to consider field observations when selecting traits for stress tolerance. Moustakas (2025) emphasizes that understanding molecular mechanisms is essential for developing abiotic stress tolerance. Samat et al. (2025) also argue that heat stress mitigation requires integration between morphological, physiological, and molecular understanding.

This study has several implications for future research. Future studies should combine qualitative fieldwork with laboratory-based molecular analysis to validate the relationship between farmer observations and biological mechanisms. Further research may also compare different crops, such as rice, maize, soybean, and horticultural plants, to identify whether similar adaptation patterns appear across species. In addition, future studies should examine combined stress more deeply because field conditions rarely produce only one type of stress. A mixed-method design that integrates interviews, field observation, physiological measurement, and gene expression analysis can produce stronger evidence for climate-resilient agriculture.

Overall, the results show that molecular adaptation mechanisms are not only relevant in laboratory-based plant science, but also in everyday agricultural practice. Farmers observe the effects of drought and salinity through visible symptoms, while molecular research explains the internal processes behind those symptoms. The connection between these two forms of knowledge can strengthen agricultural productivity under climate stress. This study therefore argues that the future of stress-tolerant agriculture requires integration between molecular biology, local farming knowledge, adaptive cultivation, and context-sensitive extension systems.

4. Conclusions

This study concludes that plant adaptation to abiotic stress is not only a biological process that occurs at the molecular level, but also a field reality that directly shapes agricultural productivity. The findings show that farmers identify drought and salinity through visible symptoms such as leaf rolling, wilting, yellowing, weak root growth, uneven plant development, and reduced grain formation. These field symptoms reflect deeper molecular processes, including hormonal regulation, osmotic adjustment, ion homeostasis, antioxidant defense, transcription factor activation, and stress memory. The study contributes to the literature by connecting farmer experiences with plant stress response theory, showing that qualitative field data can enrich the understanding of molecular adaptation mechanisms in real agroecosystem contexts.

Theoretically, this study strengthens the view that plant adaptation to abiotic stress works through an integrated response network rather than a single pathway. Practically, the findings highlight the need to translate molecular plant science into farmer-oriented extension materials, stress-tolerant crop breeding, and adaptive cultivation strategies. From a policy perspective, agricultural resilience programs should support the development and dissemination of varieties that can tolerate drought, salinity, and combined environmental stress. Future research should combine qualitative fieldwork with physiological measurement, gene expression analysis, and multi-omics approaches to validate the relationship between farmers' observations and molecular mechanisms across different crops and agroecological zones.

References

Ahmed, S. K. (2024). The pillars of trustworthiness in qualitative research. *Journal of Medicine, Surgery, and Public Health, 2*, 100051. https://doi.org/10.1016/j.glmedi.2024.100051

Aswathi, K. P. R., Ul-Allah, S., Puthur, J. T., Siddique, K. H. M., Frei, M., & Farooq, M. (2025). The plant mind: Unraveling abiotic stress priming, memory, and adaptation. *Physiologia Plantarum, 177*(4), e70372. https://doi.org/10.1111/ppl.70372

Braun, V., & Clarke, V. (2021). One size fits all? What counts as quality practice in reflexive thematic analysis? *Qualitative Research in Psychology, 18*(3), 328-352. https://doi.org/10.1080/14780887.2020.1769238

Braun, V., & Clarke, V. (2022). Conceptual and design thinking for thematic analysis. *Qualitative Psychology, 9*(1), 3-26. https://doi.org/10.1037/qup0000196

Byrne, D. (2022). A worked example of Braun and Clarke's approach to reflexive thematic analysis. *Quality & Quantity, 56*(3), 1391-1412. https://doi.org/10.1007/s11135-021-01182-y

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D., & Walker, K. (2020). Purposive sampling: Complex or simple? Research case examples. *Journal of Research in Nursing, 25*(8), 652-661. https://doi.org/10.1177/1744987120927206

Dewi, E. S., Abdulai, I., Bracho-Mujica, G., & Rötter, R. P. (2022). Salinity constraints for small-scale agriculture and impact on adaptation in North Aceh, Indonesia. *Agronomy, 12*(2), 341. https://doi.org/10.3390/agronomy12020341

Haghpanah, M., Hashemipetroudi, S., Arzani, A., & Araniti, F. (2024). Drought tolerance in plants: Physiological and molecular responses. *Plants, 13*(21), 2962. https://doi.org/10.3390/plants13212962

Iqbal, S., Wang, X., Mubeen, I., Kamran, M., Kanwal, I., Díaz, G. A., Abbas, A., Parveen, A., Atiq, M. N., Alshaya, H., Zin El-Abedin, T. K., & Fahad, S. (2022). Phytohormones trigger drought tolerance in crop plants: Outlook and future perspectives. *Frontiers in Plant Science, 12*, 799318. https://doi.org/10.3389/fpls.2021.799318

Jiang, Z., van Zanten, M., & Sasidharan, R. (2025). Mechanisms of plant acclimation to multiple abiotic stresses. *Communications Biology, 8*, 655. https://doi.org/10.1038/s42003-025-08077-w

Johnson, J. L., Adkins, D., & Chauvin, S. (2020). A review of the quality indicators of rigor in qualitative research. *American Journal of Pharmaceutical Education, 84*(1), 7120. https://doi.org/10.5688/ajpe7120

Ma, Z., Hu, L., & Jiang, W. (2024). Understanding AP2/ERF transcription factor responses and tolerance to various abiotic stresses in plants: A comprehensive review. *International Journal of Molecular Sciences, 25*(2), 893. https://doi.org/10.3390/ijms25020893

Mishra, N. M., Jiang, C., Chen, L., Paul, A., Chatterjee, A., & Shen, G. (2023). Achieving abiotic stress tolerance in plants through antioxidative defense mechanisms. *Frontiers in Plant Science, 14*, 1110622. https://doi.org/10.3389/fpls.2023.1110622

Moustakas, M. (2025). Molecular mechanisms of plant abiotic stress tolerance. *International Journal of Molecular Sciences, 26*(6), 2731. https://doi.org/10.3390/ijms26062731

Oelviani, R., Adiyoga, W., Suhendrata, T., Bakti, I. G. M. Y., Sutanto, H. A., Fahmi, D. A., Chanifah, C., Jatuningtyas, R. K., Samijan, S., Malik, A., Sahara, D., Utomo, B., Wulanjari, M. E., Winarni, E., Yardha, Y., & Aristya, V. E. (2024). Effects of soil salinity on rice production and technical efficiency: Evidence from the northern coastal region of Central Java, Indonesia. *Case Studies in Chemical and Environmental Engineering, 10*, 101010. https://doi.org/10.1016/j.cscee.2024.101010

Palmgren, M., & Shabala, S. (2024). Adapting crops for climate change: Regaining lost abiotic stress tolerance in crops. *Frontiers in Science, 2*, 1416023. https://doi.org/10.3389/fsci.2024.1416023

Roychowdhury, R., Das, S. P., Gupta, A., Parihar, P., Chandrasekhar, K., Sarker, U., Kumar, A., Ramrao, D. P., & Sudhakar, C. (2023). Multi-omics pipeline and omics-integration approach to decipher plant's abiotic stress tolerance responses. *Genes, 14*(6), 1281. https://doi.org/10.3390/genes14061281

Samat, A. T., Soltabayeva, A., Bekturova, A., Zhanassova, K., Auganova, D., Masalimov, Z., Srivastava, S., Satkanov, M., & Kurmanbayeva, A. (2025). Plant responses to heat stress and advances in mitigation strategies. *Frontiers in Plant Science, 16*, 1638213. https://doi.org/10.3389/fpls.2025.1638213

Takahashi, F., Kuromori, T., Urano, K., Yamaguchi-Shinozaki, K., & Shinozaki, K. (2020). Drought stress responses and resistance in plants: From cellular responses to long-distance intercellular communication. *Frontiers in Plant Science, 11*, 556972. https://doi.org/10.3389/fpls.2020.556972

van Zelm, E., Zhang, Y., & Testerink, C. (2020). Salt tolerance mechanisms of plants. *Annual Review of Plant Biology, 71*, 403-433. https://doi.org/10.1146/annurev-arplant-050718-100005

Yuliza, Salamah, A., & Puspitaningrum, H. (2024). Exploration of *Oryza sativa* drought-responsive element binding protein 2A (*OsDREB2A*) gene in several local Indonesian rice varieties. *Biodiversitas Journal of Biological Diversity, 25*(2), 574-582. https://doi.org/10.13057/biodiv/d250216

Zhang, H., Yu, C., Zhang, Q., Qiu, Z., Zhang, X., Hou, Y., & Zang, J. (2025). Salinity survival: Molecular mechanisms and adaptive strategies in plants. *Frontiers in Plant Science, 16*, 1527952. https://doi.org/10.3389/fpls.2025.1527952

Zhou, W., Wang, M., Wang, L., Liu, Y., Tian, Z., Xie, L., & Wang, Y. (2025). Epigenetics in plant response to climate change. *Biology, 14*(6), 631. https://doi.org/10.3390/biology14060631