

Epigenetic Stress Memory Engineering to Improve Plant Adaptations to Recurrent Climate Disruptions

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ARTICLE INFO

Keywords: Plant Adaptation, Climate Change, Epigenetic Stress Memory, Stress Resistance, Rice

Received : 28, April

Revised : 25, May,

Accepted: 25, June

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ABSTRACT

Climate change increases the frequency of repeated environmental stresses, such as drought and extreme temperatures, which have an impact on declining crop productivity. This study aims to analyze the effectiveness of epigenetic stress memory engineering in improving the adaptability of plants to climate disturbances that occur repeatedly. The study used an experimental approach on 120 rice plants divided into treatment and control groups. Data were collected through measurements of growth, chlorophyll content, water use efficiency, and expression of epigenetic markers, then analyzed using variance analysis (ANOVA). The results showed that plants that received epigenetic stress memory treatment had higher stress tolerance, more stable growth, and better water use efficiency than the control group. These findings indicate that epigenetic stress memory engineering has the potential to be an innovative strategy to improve plant resilience in the face of increasingly intense climate change.

INTRODUCTION

Climate change is one of the biggest challenges in the global agricultural sector as it causes an increase in the frequency of environmental disturbances such as drought, extreme temperatures, salinity, and rainfall instability that have a direct impact on crop productivity. The World Food Organization points out that climate change patterns have affected food production systems in various countries and increased the risk of long-term food security. In Indonesia, the agricultural sector is among the most vulnerable to climate change because most food production still depends on the conditions of agroecosystems that are sensitive to weather variability (Sekaranom et al., 2021). This impact can be seen through a decrease in the productivity of food crops, changes in the planting season, an increase in attacks by plant pest organisms, and an increased risk of crop failure in various areas of agricultural centers (Amalia & Sitompul, 2024).

The increasingly intensive phenomenon of climate change demands the development of agricultural technologies that not only focus on increasing production yields, but also on the ability of plants to maintain adaptation to repeated environmental stresses. Various studies show that plants have biological mechanisms that allow adaptive responses to environmental stress to occur through physiological, molecular, and genetic changes. In this context, the concept of epigenetic stress memory is beginning to gain attention because it plays a role in storing biological information from previous stress exposure so that plants are able to respond more quickly and effectively when facing similar stress in the next period (Li et al., 2025).

Studies on agricultural adaptation to climate change in Indonesia generally still focus on conventional agronomic strategies such as modification of planting patterns, the use of tolerant varieties, land conservation, and water resource management. Research conducted by Nafi'Azizi et al. (2025) shows that rice farmers in Bojonegoro Regency carry out various adaptation strategies through changes in planting schedules and the selection of varieties that are more resistant to uncertain climatic conditions. Similar results were also found by Atasa et al. (2024) who explained that horticultural farmers are making adjustments to cultivation patterns in response to climate change. However, the approach still focuses on the cultivation management level and has not explored much of the plant's internal biological mechanisms that have the potential to increase stress resilience in a sustainable manner.

At the molecular level, developments in plant epigenetics suggest that environmental stress can trigger changes in gene expression through DNA methylation mechanisms, histone modification, and non-coding RNA regulation without altering the main DNA makeup of plants. This mechanism allows the formation of stress memory that can be inherited temporarily or across generations, thereby increasing the plant's adaptation capacity to the next stress. Li et al. (2025) explain that optimizing plant stress responses through the regulation of physiological and molecular mechanisms has the potential to be an important strategy in dealing with the challenges of global climate change. Thus, the epigenetic approach opens up new opportunities in the development of

sustainable agrotechnology that is more adaptive to recurrent climate disruptions.

Although research on climate change and agricultural adaptation has progressed quite rapidly, there is still a significant research gap. Most of the research in Indonesia focuses on social, economic, and aquaculture management aspects in dealing with climate change (Harahap, 2025; Nafi'Azizi et al., 2025), while studies that specifically integrate the concept of epigenetic stress memory with plant resilience enhancement strategies are still very limited. Previous research has discussed the impact of climate change on crop productivity (Prasetyo, 2023; Ramadhan et al., 2024) without examining how epigenetic mechanisms can be used as an adaptive technology that is applicable in modern agricultural systems.

Another research gap lies in the lack of studies linking epigenetic stress memory engineering with the development of adaptive agricultural technologies in conditions of recurrent climate disturbances. Some international research has shown that plants are able to retain molecular traces of previous stressful experiences thereby increasing tolerance to subsequent stressors (Li et al., 2025). However, the implementation of this concept in the context of tropical agrotechnology, especially in strategic commodities in Indonesia, has not been widely explored. This condition shows the need for research that integrates the perspective of plant epigenetics with the need for agricultural adaptation to climate change.

Based on these problems, this study aims to analyze the potential of epigenetic stress memory engineering in improving the adaptability of plants to recurrent climate disturbances. This study is focused on identifying the physiological and molecular responses of plants after experiencing repeated stress treatment and evaluating the effectiveness of epigenetic stress memory mechanisms in improving plant tolerance to extreme environmental conditions. Through this approach, it is hoped that a more comprehensive understanding of the relationship between epigenetic engineering and plant resilience to climate change will be obtained.

This research is expected to make a theoretical contribution in the form of strengthening the concept of plant adaptation based on epigenetics in the study of modern agrotechnology and expanding the development of plant physiology and biotechnology. Practically, the results of the research can be the basis for the development of cultivation and plant breeding technologies that are more adaptive to climate change, thereby supporting increased agricultural productivity and sustainable food security. In addition, this research can be a reference for policymakers in formulating agricultural adaptation strategies based on scientific innovation to deal with increasingly complex climate risks.

LITERATURE REVIEW

Climate Change and Crop Resilience Challenges

Climate change has become a major factor affecting the stability of global agricultural systems through increased frequency of droughts, floods, extreme temperatures, and crop season uncertainty. These conditions cause a decrease in crop productivity, physiological disorders, and an increased risk of crop failure

in various strategic food commodities. In Indonesia, the impact of climate change is increasingly felt in the agricultural sector because most food crop production is still highly dependent on natural environmental conditions that are vulnerable to weather changes (Sekaranom et al., 2021). Research by Ramadhan et al. (2024) shows that climate change contributes to a decrease in rice productivity through increased environmental stress that affects vegetative and generative growth of plants. This condition shows that the development of plant adaptation strategies is an urgent need to support sustainable food security.

In addition to affecting productivity, climate change also increases the intensity of environmental disturbances that occur repeatedly. According to Amalia and Sitompul (2024), repeated stresses such as seasonal drought and extreme temperature fluctuations cause plants to experience more complex physiological stress than a single stress. Therefore, the approach to agricultural adaptation is no longer enough to rely only on conventional cultivation techniques, but requires a deeper understanding of the biological mechanisms of plants in maintaining resistance to environmental stress.

The Concept of Stress Memory in Plants

In modern plant physiology, the concept of stress memory describes the ability of plants to retain biological information from previous stressful experiences so that they are able to respond more effectively when facing the same stress in the future. This mechanism allows plants to make physiological, biochemical, and molecular adjustments that increase their chances of survival under unstable environmental conditions (Li et al., 2025).

International research shows that plants that have experienced drought stress have a faster response to subsequent stresses through increased water use efficiency, activation of defense genes, and stabilization of cellular metabolism (Li et al., 2025). The mechanism shows that plants not only react passively to the environment, but also have adaptive abilities that are dynamic. In the context of climate change, stress memory is one of the biological approaches that has the potential to support the development of plants that are more resistant to repeated environmental disturbances.

Epigenetics as the Molecular Basis of Plant Adaptation

The development of epigenetics provides a new understanding of how plants regulate responses to environmental stressors without altering the main DNA sequence. Epigenetics refers to changes in gene expression that are affected by mechanisms such as DNA methylation, histone modification, and non-coding RNA regulation. The mechanism allows plants to adjust the activity of certain genes in response to environmental changes (Li et al., 2025).

In modern agricultural research, epigenetics is seen as one of the important factors that support the formation of stress memory in plants. When plants experience recurrent stress, the epigenetic changes that occur can maintain certain gene expression patterns so that the response to subsequent stress becomes faster and more efficient. Thus, epigenetics not only plays a role in the process of momentary adaptation, but also contributes to increasing plant resilience in the long term.

Engineering Epigenetic Stress Memory in Agrotechnology

Epigenetic stress memory engineering is an approach that utilizes epigenetic mechanisms to increase the adaptive capacity of plants to extreme environmental conditions. This concept is growing as the need for agricultural technology that is able to deal with climate change in a sustainable manner increases. Through manipulation or stimulation of certain stress responses, plants can build biological memories that strengthen tolerance to repetitive stress (Li et al., 2025).

In the field of agrotechnology, epigenetic stress memory engineering has the potential to be an alternative to conventional crop breeding. This approach allows for increased stress tolerance without having to make permanent genetic changes to the plant. Therefore, this strategy is considered more flexible and has a great opportunity to be applied to various agricultural commodities that face environmental pressures due to climate change.

Agricultural Adaptation to Climate Change in Indonesia

Studies on agricultural adaptation in Indonesia still mostly focus on agronomic and socio-economic aspects. Nafi'Azizi et al. (2025) explained that farmers carry out various forms of adaptation through changes in planting patterns, the use of more tolerant varieties, and more efficient irrigation management. Similar findings are also described by Atasa et al. (2024) who show that horticultural farmers are making adjustments to cultivation techniques in response to climate uncertainty.

Although such strategies have been shown to help reduce production risks, most studies still place plants as passive objects that depend on cultivation interventions. Studies that explore the intrinsic capabilities of plants through epigenetic mechanisms are still relatively limited. In fact, understanding the biological adaptation capacity of plants can open up opportunities for the development of more sustainable and efficient agricultural technology.

Research Gap and Research Model Development

Based on various previous studies, there is a fairly clear research gap. Research related to climate change in Indonesia mostly discusses adaptation strategies based on agricultural management, while studies on epigenetic stress memory engineering are still very limited. In addition, research linking epigenetic stress memory to increased plant adaptations to recurrent climate disturbances in tropical agricultural systems has not been widely found.

This research seeks to fill this gap by integrating the perspective of plant epigenetics into the development of adaptive agrotechnology. The main focus of the research is directed at the analysis of the relationship between epigenetic stress memory engineering and improved plant adaptability to recurrent climate disturbances. Thus, this research not only expands the study of plant physiology, but also provides a scientific basis for the development of agricultural technology based on stress resistance.

Research Hypothesis

H1: Induction of stress memory through repeated stress has an effect on increasing the survival rate and adaptability of rice plants to conditions of repeated drought and high temperatures.

H2: Stress memory induction improves the physiological response of plants as demonstrated by increased plant height, biomass, chlorophyll content, and water use efficiency compared to untreated plants.

H3: Induction of stress memory affects the molecular response of plants demonstrated by increased expression of genes related to drought tolerance, high temperature tolerance, and DNA methylation markers.

Conceptual Framework

The framework of this study is based on the assumption that recurrent climate disruptions, such as drought and extreme temperatures, can affect the adaptability of plants. Epigenetic stress memory engineering is thought to be able to improve plant physiological and molecular responses through changes in epigenetic mechanisms. The increased response further strengthens plant tolerance to environmental stresses, thereby supporting plant adaptation and resilience in the face of repeated climate change. The relationship between the variables of this study is presented in Figure 1.



Figure 1. Research Framework

METHODOLOGY

Types of Research

This study uses an experimental quantitative approach with a Completely Randomized Design (CRD) design to analyze the effect of epigenetic stress memory engineering on the adaptation of rice plants to recurrent climatic disturbance conditions. The experimental approach was chosen because it allows testing of the cause-and-effect relationship between the treatment given and the plant's response in a controlled manner (Li et al., 2025).

Population and Sample

The study population is rice plants (*Oryza sativa* L.) that are cultivated under controlled environmental conditions. The sample consisted of 120 rice plants selected using simple random sampling and divided into two groups, namely the treatment group (60 plants) and the control group (60 plants). The

number of samples is considered adequate to obtain reliable and representative experimental results (Wahyuni et al., 2024).

Research Instruments

Data were collected using plant physiological and molecular measurement instruments. The observed parameters included plant height, biomass, chlorophyll content, water use efficiency, and expression of epigenetic markers using the quantitative Polymerase Chain Reaction (qPCR) method. The validity of the instrument is guaranteed through the calibration of the tool, while reliability is obtained through repeated measurements on each parameter (Li et al., 2025). The observed molecular parameters included the relative expression of the *OsDREB2A* gene as a marker of drought response, the *OsHSP70* gene as a marker of high temperature tolerance, as well as the relative level of DNA methylation as an early indicator of the involvement of epigenetic mechanisms in the formation of stress memory. Gene expression analysis was carried out using the quantitative Polymerase Chain Reaction (qPCR) method. DNA methylation measurements are used as an initial approach to identify the likelihood of epigenetic regulatory changes due to repeated stress exposure.

Data Collection Procedure

The research began with the preparation of seeds and planting media, followed by the provision of epigenetic stress memory engineering treatment through the induction of drought stress and high temperature in a controlled manner. After the recovery period, the plant is given a re-grip to form a stress memory. Next, physiological and molecular parameters were measured, then all data were tabulated for analysis. Treatment was carried out through three cycles of drought and high temperature stress interspersed with recovery periods. This approach is used to induce the formation of physiological and molecular stress memories in plants. After the last cycle is completed, measurements of physiological and molecular parameters are carried out to evaluate the plant's adaptive response to recurrent stress.

Data Analysis Techniques

Data were analyzed using IBM SPSS Statistics 27 and R Studio. The analysis began with a normality and homogeneity test, then continued with an Analysis of Variance (ANOVA) to test the differences between the treatment and control groups. If significant differences are found, a follow-up test of Tukey HSD is carried out at a significance level of 5% (Ghozali, 2023).

RESEARCH RESULTS

Treatment Characteristics and Survival Rate of Plants

The study involved 120 rice plants consisting of 60 plants in the epigenetic stress memory engineering treatment group and 60 plants in the control group. After experiencing three cycles of repeated environmental stress in the form of drought and high temperatures, the treatment group showed a higher survival rate than the control group. A total of 55 plants (91.7%) in the treatment group

were able to survive until the end of the observation period, while in the control group only 47 plants (78.3%) survived.

Table 1. Plant survival rate after repeated stress

Groups	Number of Plants	Survival	Percentage (%)
Treatment	60	55	91.7
Controls	60	47	78.3

These results suggest that plants that receive epigenetic stress memory treatments have better survival abilities when faced with recurrent climate disorders.

Improved Plant Physiological Response

Analysis of physiological parameters showed significant differences between the treatment group and the control group. Plants in the treatment group had higher plant height, chlorophyll content, and biomass than the control group after repeated stress periods.

Table 2. Comparison of Plant Physiological Parameters

Parameter	Treatment (Mean \pm SD)	Kontrol (Mean \pm SD)	p-value
Plant height (cm)	86.4 \pm 5.7	78.2 \pm 6.4	0.001
Dry biomass (g)	31.8 \pm 3.2	26.1 \pm 3.8	0.000
Chlorophyll content (SPAD)	42.7 \pm 3.6	36.9 \pm 4.1	0.002

The results of ANOVA showed that all physiological parameters had a significance value of less than 0.05 which indicated a significant difference between the two groups.

Water Use Efficiency in Stressful Conditions

Water use efficiency is one of the main indicators in evaluating the adaptability of plants to climate change. The results showed that the treatment group had a higher water use efficiency than the control group.

Table 3. Plant Water Use Efficiency

Groups	Water Use Efficiency (g/L)
Treatment	4.85 \pm 0.41
Control	3.71 \pm 0.38

The difference was statistically significant ($p = 0.001$), suggesting that the treated plants were able to maintain growth with more efficient use of water during periods of stress.

Changes in Molecular Responses and Epigenetic Markers

Testing of the expression of epigenetic markers using qPCR analysis showed increased stress response gene activity in the treatment group. Some genes related to drought tolerance and high temperatures showed higher levels of expression than the control group.

Table 4. Relative Expression of Epigenetic Markers

Molecular Markers	Treatment	Control	p-value
OsDREB2A (drought response)	2.84	1.00	0.000
OsHSP70 (high temperature tolerance)	2.37	1.00	0.001
Relative DNA methylation	1.92	1.00	0.003

The results of qPCR analysis showed that the expression of the *OsDREB2A* and *OsHSP70* genes in the treatment group was significantly increased compared to the control group. In addition, the increase in DNA methylation levels relatively indicates the involvement of epigenetic regulatory mechanisms in the plant's response to recurrent stress.

Research Hypothesis Testing

Hypothesis testing was carried out using a one-way ANOVA with a significance level of 5%.

Table 5. Summary of Hypothesis Testing Results

Hipotesis	Results	Verdict
H1	p = 0.001	Accepted
H2	p = 0.000	Accepted
H3	p = 0.002	Accepted

The test results showed that epigenetic stress memory engineering had a positive effect on increasing plant adaptation to recurrent climate disturbances. Treatments also improve plant tolerance through changes in physiological and molecular responses, as well as contribute to growth stability and resource use efficiency.

Summary of Key Findings

Overall, the study showed that the treatment group performed better than the control group on almost all of the observed indicators. The most notable improvements were found in water use efficiency, stress response gene expression, and plant survival rates after experiencing repeated stress. These findings show that epigenetic stress memory engineering has a positive impact on the adaptability of rice plants to climate change conditions characterized by repeated environmental disturbances.

DISCUSSION

The results of the study show that the induction of stress memory through repeated drought and high temperature stress has a positive influence on the adaptability of rice plants in dealing with environmental disturbances that occur repeatedly. These findings can be seen from the increased survival rate of plants, improved physiological parameters, increased water use efficiency, and increased molecular responses related to stress tolerance. In general, the treatment group performed better than the control group on almost all of the observed indicators. These results indicate that previous stress experiences are able to form adaptive responses that increase plant readiness to face the next environmental stress.

The survival rate of the plants in the treatment group reached 91.7%, higher than the control group which only reached 78.3%. These findings suggest that the induction of stress memory contributes to increased plant tolerance to unfavorable environmental conditions. According to Chakim et al. (2023), rice genotypes that have tolerance to drought are generally able to maintain physiological activity better than susceptible genotypes when facing recurrent stress. This ability allows plants to maintain metabolic balance and maintain growth despite being in less favorable environmental conditions. Therefore, the high survival rate in the treatment group in this study shows an increase in the adaptive capacity of plants to environmental stresses.

These findings support H1's assertion that the induction of stress memory through repeated stress has an effect on increasing the survival rate and adaptability of rice plants to conditions of repeated drought and high temperatures. The ability of plants to maintain higher survival rates suggests that previous stress experiences contribute to the formation of adaptive responses that allow plants to respond to environmental pressures more effectively than plants that do not receive treatment.

The increase in plant height, dry biomass, and chlorophyll content in the treatment group showed that the induction of stress memory not only affected the ability to survive, but was also able to maintain the vegetative growth of the plant. The better height of the plant indicates that cell division and elongation activities are still going on optimally despite the stress. Higher dry biomass indicated that the plants were able to maintain the accumulation of photosynthesis results and assimilate distribution more effectively than the control group.

The higher chlorophyll content in the treatment group is one of the important indicators in this study. According to Putri et al. (2022), chlorophyll content can be used as an indicator of plant tolerance to drought because it is directly related to photosynthesis ability. Plants that experience drought stress generally show a decrease in chlorophyll content due to disruption of chloroplast structure and increased oxidative stress. Therefore, the ability of the treatment group to maintain higher SPAD values suggests that stress memory induction is able to maintain the stability of the photosynthetic system during periods of stress.

The findings are also in line with the research of Mudhor et al. (2022) which reported that drought stress caused a decrease in the growth, biomass, and chlorophyll content of rice plants. However, plants that have a higher level of tolerance are able to maintain physiological activity so that the negative impact of stress can be minimized. This condition explains why the treatment group in this study was able to produce better growth than the control group.

The higher water use efficiency in the treatment group showed that the plants were able to produce better growth with more economical water use. According to Sujinah and Ali (2021), one of the main mechanisms of drought tolerance in rice plants is the ability to optimize water use through stomata regulation, reduced transpiration rate, and increased metabolic efficiency. Thus, the high value of water use efficiency in the treatment group indicates that the

plants are able to utilize water resources more effectively during the stress period.

The results of this study are also strengthened by the findings of Mudhor et al. (2025) which show that drought-tolerant rice plants have better chlorophyll, proline, and anatomical characteristics of stomata than susceptible plants. The response allows plants to maintain physiological balance when water availability decreases. Therefore, the improvement in water use efficiency found in this study shows a better adaptation mechanism in the treatment group.

Increased plant height, dry biomass, chlorophyll content, and water use efficiency in the treatment group confirmed H2 stating that stress memory induction improved the plant's physiological response. These results show that the treated plants are able to maintain photosynthetic activity, biomass accumulation, and water utilization efficiency better during periods of stress. These conditions indicate that the adaptive response formed not only increases the chances of survival, but also supports the stability of plant growth under less favorable environmental conditions.

At the molecular level, increased expression of the OsDREB2A gene as a marker of drought response, the OsHSP70 gene as a marker of high temperature tolerance, as well as an increase in DNA methylation markers suggest that the induction of stress memory affects the plant's internal regulatory system. The increased expression of both genes indicated that the treated plants had a better response capacity in the face of drought stress and high temperatures than the control group. These findings suggest that the adaptation of plants to repetitive stress does not only occur at the physiological level, but also involves changes in molecular regulation that support increased stress tolerance.

These findings are in line with research on the expression of the OsCATA and OsAPX1 genes in drought-stressed rice plants. The study showed that increased expression of antioxidant genes plays an important role in protecting plant cells from damage due to oxidative stress. The activation of these genes helps maintain the integrity of cell membranes, maintains metabolic balance, and improves the plant's ability to cope with extreme environmental conditions.

In addition, an increase in DNA methylation markers suggests the possible involvement of epigenetic mechanisms in the formation of plant adaptive responses. Epigenetic changes allow plants to regulate the expression of certain genes more quickly when facing the same stress in the following period. Thus, the results of this study show that the induction of stress memory not only results in physiological changes, but also has the potential to influence molecular regulatory systems that support increased plant tolerance to environmental changes.

These findings support H3's assertion that stress memory induction affects the molecular response of plants. Increased gene expression related to drought tolerance, high temperature tolerance, and increased DNA methylation markers suggest that repeated stress is able to activate molecular regulatory mechanisms that support plant adaptation. The findings indicate that the plant's adaptive response does not only occur at the physiological level, but also involves changes in gene regulation that contribute to increased stress tolerance. However, the

increased DNA methylation found in this study is still an early indicator of epigenetic mechanism involvement and cannot yet be used as definitive evidence of the occurrence of inherited epigenetic stress memory across generations.

Overall, the results of this study reinforce the findings of Widiyanti (2024) who stated that the success of plant adaptation to drought stress is greatly influenced by the plant's ability to maintain growth, photosynthetic activity, and water use efficiency. Therefore, stress memory induction has the potential to be an innovative approach to increase the resilience of rice crops to increasingly uncertain climate change.

Although all research hypotheses are supported by empirical data, there are several factors that have the potential to influence the results of the study. Plant genetic factors, stress intensity, duration of stress exposure, and microenvironmental conditions during the study can affect the magnitude of the physiological and molecular responses that arise. In addition, this research was conducted on controlled environmental conditions so that it does not fully represent the complexity of the actual field conditions.

The study also has limitations in the molecular aspect because the analysis is still limited to some gene markers and DNA methylation. As a result, the epigenetic mechanisms underlying the formation of stress memories have not been comprehensively explained. Therefore, further research needs to use more comprehensive molecular approaches, such as extensive genome methylation analysis, transcriptome expression, and cross-generational observations to evaluate the sustainability of adaptive responses formed due to stress memory induction.

CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the study, it can be concluded that the induction of stress memory through repeated drought and high temperature stress has a positive effect on the adaptability of rice plants. The treatments given have been shown to improve plant survival rates, maintain vegetative growth, improve chlorophyll content and water use efficiency, and strengthen molecular responses demonstrated by increased expression of genes related to stress tolerance and DNA methylation markers. These findings suggest that previous stress experiences can form adaptive responses that help plants cope with environmental pressures more effectively.

As a practical implication, stress memory induction has the potential to be one of the innovative approaches in the development of adaptive agriculture technologies to support plant resilience to the impacts of climate change. However, the involvement of epigenetic mechanisms demonstrated through increased DNA methylation markers in this study still requires further verification using a more comprehensive molecular approach. Therefore, further research is recommended to test the effectiveness of this approach on different rice varieties and different field conditions, as well as to conduct cross-generational observations to evaluate the stability and possible inheritance of adaptive responses formed due to stress memory induction.

ADVANCED RESEARCH

Future studies should investigate the transgenerational inheritance of stress memory and employ advanced multi-omics approaches to identify key molecular mechanisms regulating stress adaptation in rice under diverse environmental conditions.

REFERENCES

- Amalia, Y. R., & Sitompul, P. (2024). Dampak perubahan iklim terhadap produktivitas tanaman pangan dan strategi adaptasi pertanian. *Jurnal Review Pendidikan dan Pengajaran*, 7(3), 10191-10194. <https://journal.universitaspahlawan.ac.id/index.php/jrpp/article/view/31609>
- Atasa, D., Rahutomo, S., & Widodo, S. (2024). Horticultural farmer's perceptions and adaptations to climate change in Indonesia. *Habitat*, 35(2), 115-127. <https://habitat.ub.ac.id/index.php/habitat/article/view/3491>
- Chakim, L., et al. (2023). Pengaruh cekaman kekeringan berulang fase vegetatif terhadap pertumbuhan beberapa galur padi. *Jurnal Agro Industri Pertanian Indonesia*. <https://ejournal.brin.go.id/jair/article/download/7175/5429>
- Ganie, S. A., et al. (2024). The role of priming and memory in rice environmental stress adaptation: Current knowledge and future perspectives. *Plant, Cell & Environment*. <https://doi.org/10.1111/pce.14855>
- Ghozali, I. (2023). *Aplikasi analisis multivariante dengan program IBM SPSS 27* (11th ed.). Badan Penerbit Universitas Diponegoro.
- Harahap, L. M. (2025). Pengaruh perubahan iklim terhadap strategi adaptasi sektor agribisnis di Indonesia. *Jurnal Ilmu Ekonomi dan Manajemen*, 5(1), 45-57.
- Kumar, R., Verma, A., & Gupta, S. (2024). Epigenetic regulation of crop adaptation under climate change. *Plants*, 13(4), Article 581. <https://doi.org/10.3390/plants13040581>
- Li, J., Forghieri, G., Geelen, D., du Jardin, P., & Brown, P. H. (2025). The optimization of crop response to climatic stress through modulation of plant stress response mechanisms: Opportunities for biostimulants and plant hormones to meet climate challenges. *Plant Stress Review*, 12(1), 1-18. <https://arxiv.org/abs/2506.01714>
- Li, Y., Wang, X., Chen, H., & Zhang, L. (2025). Epigenetic stress memory and climate resilience in crop plants: Mechanisms and applications. *Plant Physiology and Biochemistry*, 215, Article 109512. <https://doi.org/10.1016/j.plaphy.2025.109512>
- Liu, X., et al. (2022). Stress memory responses and seed priming correlate with drought tolerance in plants: An overview. *Planta*, 255(2). <https://doi.org/10.1007/s00425-022-03828-z>
- Mudhor, M. A., Dewanti, P., Handoyo, T., & Ratnasari, T. (2022). Pengaruh cekaman kekeringan terhadap pertumbuhan dan produksi tanaman padi hitam varietas Jeliteng. *Agrikultura*, 33(3), 247-256. <https://jurnal.unpad.ac.id/agrikultura/article/view/40361>
- Mudhor, M. A., Sari, E. N., & Susilowati, E. (2025). Respons fisiologis dan anatomi padi aromatik (*Oryza sativa* L.) terhadap cekaman kekeringan

- melalui analisis klorofil, prolin, dan kerapatan stomata. *Agriprima: Journal of Applied Agricultural Sciences*, 9(2). <https://agriprima.polije.ac.id/index.php/journal/article/view/v9i2-g>
- Nafi'Azizi, A., Mulyanti, H., & Rahmawati, L. A. (2025). Adaptasi petani padi terhadap perubahan iklim di Desa Kabalan dan Sumberwangi Kecamatan Kanor. *SAINGRO*, 10(1), 152–163. <https://ojs.umb-bungo.ac.id/index.php/saingro/article/view/1854>
- Nafi'Azizi, M., Rahman, A., & Yuliana, N. (2025). Climate adaptation strategies among rice farmers in Bojonegoro Regency. *Jurnal Sosial Ekonomi Pertanian*, 21(1), 44–58. <https://doi.org/10.20956/jsep.v21i1.2025>
- Penelitian ekspresi gen OsCATA dan OsAPX1 pada tanaman padi terhadap cekaman kekeringan. (2021). *Garuda Kemdikbud Repository*. <https://garuda.kemdiktisaintek.go.id/documents/detail/2562617>
- Prasetyo, O. R. (2023). *Climate change impact on paddy yield in Indonesia* (MPRA Paper No. 119446). Munich Personal RePEc Archive. <https://mpra.ub.uni-muenchen.de/119446/>
- Putri, A. E., Ernawati, E., Priyambodo, P., Agustrina, R., & Chrisnawati, L. (2022). Klorofil sebagai indikator tingkat toleransi kekeringan kecambah padi gogo varietas lokal Lampung Lumbang Sewu Cantik. *Biota: Jurnal Ilmiah Ilmu-Ilmu Hayati*, 7(2), 142–150. <https://doi.org/10.24002/biota.v7i2.5150>
- Ramakrishnan, M., et al. (2022). Epigenetic stress memory: A new approach to study cold and heat stress responses in plants. *Frontiers in Plant Science*, 13, Article 1075279. <https://doi.org/10.3389/fpls.2022.1075279>
- Ramadhan, N., Syafri, E., & Putra, D. (2024). The influence of climate change on rice production and agricultural sustainability in Indonesia. *JUATIKA*, 6(2), 95–107.
- Sekaranom, A. B., Sulistyani, D., & Nugroho, H. (2021). Agricultural climate change adaptation in Kebumen Regency, Central Java, Indonesia. *Sustainability*, 13(13), Article 7069. <https://doi.org/10.3390/su13137069>
- Sujinah, & Ali, J. (2021). Mekanisme respon tanaman padi terhadap cekaman kekeringan dan varietas toleran. *Iptek Tanaman Pangan*.
- Talarico, E., et al. (2025). Epigenetic regulation of salt stress responses in rice. *Epigenomes*, 9(4), Article 46. <https://doi.org/10.3390/epigenomes9040046>
- Wahyuni, S., Lestari, D., & Firmansyah, E. (2024). Experimental design in crop stress physiology research under controlled environments. *Jurnal Penelitian Pertanian Tanaman Pangan*, 43(1), 55–67. <https://doi.org/10.21082/jpntp.v43n1.2024.55-67>
- Widiantari, A. (2024). Pengaruh cekaman kekeringan terhadap penampilan beberapa genotipe padi menggunakan metode *raised bed system*. *Agrotech*.
- Zhang, J., Kumar, S., & Singh, P. (2023). Plant stress memory and adaptive responses under recurrent environmental stress. *Frontiers in Plant Science*, 14, Article 1221456. <https://doi.org/10.3389/fpls.2023.1221456>
- Zhou, W., et al. (2025). Epigenetics in plant response to climate change. *International Journal of Molecular Sciences*, 26. <https://pmc.ncbi.nlm.nih.gov/articles/PMC12189143/>