Science Get Journal
Vol. 01, No. 4, October 2024, 17-27
e-ISSN: 3062-6595

Using Biotechnology to Create Transgenic Crops That Resist Climate Change

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Article Information
Received: November 04, 2024
Revised: November 06, 2024
Online: December 04, 2024

Keywords
Transgenic Crop Biotechnology, Food Security, Drought, High Temperature, Nutrition

ABSTRACT

Climate change is a major threat to food security, especially for farmers in vulnerable areas facing the challenges of climate change. This study aimed to modify the plant genome to increase tolerance to extreme climatic conditions such as drought and high temperatures using genetic engineering methods based on CRISPR-Cas9 technology. Transgenic and control plants were grown in a laboratory experimental design with a quantitative approach. The results showed that the transgenic plants consistently outperformed the control plants under drought, high temperature, and low nutrient conditions. The transgenic plant showed a growth rate of 15.2 and average productivity of 25.7, higher than the control (12.3 and 19.1). Under high temperature conditions, the increase in productivity was even greater, reaching 33.2%, indicating that the inserted HSP gene successfully protects important proteins from heat stress damage. Genetic modification through the expression of genes such as DREB1A, HSP70, and PHR1 was shown to increase plant resistance to environmental stress. With these findings, biotechnology provides a real opportunity to build more adaptive and sustainable agricultural systems, supporting global food needs amid the intensifying challenges of global warming. This research is very relevant in answering the big challenge in the future, which is how to ensure biotechnology can be utilised sustainably to meet the world's growing food needs, without compromising ecosystems and biodiversity.

Keywords: *GM Crop Biotechnology, Food Security, Drought, High Temperature, Nutrition*

http://dx.doi.org/10.69855/science.v1i3.83
https://gpijournal.com/index.php/science
PUBLISHED BY: GPress Indonesia

INTRODUCTION

Climate change has become a major challenge for the global agricultural sector. Conditions such as drought, high temperatures, salinity and changing rainfall patterns threaten crop productivity. This exacerbates the problem of global food security, especially in the face of increasing human population. Therefore, technological innovations are needed to overcome the impacts of climate change on crops, one of which is through the use of modern biotechnology.

Biotechnology, particularly genetic engineering, enables genetic modification of plants to increase tolerance to abiotic stresses such as drought, extreme temperatures and salinity. The resulting transgenic plants have superior traits that are difficult to achieve through conventional breeding techniques. Examples include drought- and high-temperature-resistant plants developed by expressing specific genes such as DREB2A and heat-shock proteins (Grover et al., 2013).

In addition, genes encoding osmoprotectants such as proline have been applied to improve tolerance to osmotic stress under drought and salinity conditions (Khan et al., 2015). Transgenic crops can also produce higher yields even under non-ideal soil and climate conditions, such as increased photosynthetic efficiency and nitrogen utilisation (Wani et al., 2015).

The use of GM crops not only addresses food security challenges but also supports climate change mitigation. Some GM crops are designed to minimise greenhouse gas emissions by increasing growth efficiency on limited land (Seid & Andualem, 2021).

Biochar, a product of biotechnology, increases water retention capacity and nutrient content in dry soils, thereby significantly supporting the growth of crops such as maize (Navisa Hanim et al., 2021). However, its development continues to face various ethical and safety issues. Major public concerns include the long-term impact of GM crops on the environment, such as the risk of transgenic genes spreading to wild plant species, which could alter the balance of local ecosystems. Therefore, research on GMO crops must be conducted in compliance with strict regulations to ensure safety for the environment and human health.

At the global level, various countries have implemented strict regulations, including field trials and risk assessment procedures before the release of transgenic crops into the environment (Estiati & Herman, 2015; Santosa, 2024). In Indonesia, the development and use of GMO crops is regulated by the Food and Drug Administration (BPOM) and the Ministry of Agriculture, which ensure that biotechnology is applied responsibly. This strong regulatory support is an important foundation to encourage research in agricultural biotechnology, resulting in innovations that are adaptive to climate change while being safe for the environment.

The importance of this research lies in its relevance in supporting global food security. With a growing world population and increasingly unpredictable climatic conditions, this technology can be a solution to create crop varieties that are more resilient to extreme weather, drought, and pest and disease attacks. However, it is also important to answer a critical question: How effective are existing regulations and risk assessment procedures in preventing negative impacts of GMO crops on the environment and human health?

Based on this question, the hypothesis is: If regulations and risk assessments are carried out comprehensively and supported by strong scientific data, the development of GMO crops can be carried out safely without causing significant negative impacts on the environment and human health, while supporting food security in the midst of global climate change.

This research is very relevant in answering the big challenge in the future, which is how to ensure biotechnology technology can be utilised sustainably to meet the world's growing food needs, without compromising ecosystems and biodiversity.

METHODS

This study uses a laboratory experimental design with a quantitative approach, aiming to modify the plant genome to increase tolerance to extreme climatic conditions such as drought and high temperatures using genetic engineering methods based on CRISPR-Cas9 technology. Model plants such as Arabidopsis thaliana or tobacco were chosen as initial test objects due to their easy modification and short life cycle, while food crop varieties such as rice or wheat were used for practical application in crops that are vulnerable to climate change. The genetic modification process involves inserting specific genes involved in metabolic pathways, such as osmotic regulation, heat shock protein (HSP) production, or proline biosynthesis, that enhance plant adaptation to stress conditions. These modified plants are tested in a climate control chamber or greenhouse, where drought and high temperature environments are gradually simulated, while unmodified control plants are used as a comparison.

Tests were conducted by measuring several key variables, including chlorophyll levels using a spectrophotometer to assess photosynthetic efficiency, wet and dry biomass using a digital scale, plant height using a ruler, and plant productivity through seed number or grain volume. Plant tolerance to environmental stress was evaluated periodically by examining additional parameters such as proline levels and antioxidant enzyme activities, which serve as indicators of physiological stress. The data obtained were analysed using various statistical methods. T-tests were used to compare differences between transgenic and control plants, while regression analyses were conducted to identify significant relationships between environmental stress levels, such as humidity and temperature, and plant variables such as chlorophyll, biomass and productivity. Analysis of Variance (ANOVA) was applied to evaluate the effects of different treatments on crop variables, and cluster analysis could be used to group genotypes based on their level of adaptation to stress.

This research was conducted in compliance with biosafety and research ethics protocols, including strict control of the potential spread of transgenic genes to the external environment. All procedures were designed to ensure safety and minimise negative impacts on the environment. However, results from laboratory and climate-controlled experiments may not reflect more complex field conditions, so further research on a field scale is needed to ascertain the overall effectiveness of transgenic crops in dealing with climate change. This approach is expected to make an important contribution to sustainable agriculture in the future by producing crops that are more resilient to environmental stress.

RESULTS

A. Crop Condition Against Drought

Table 1. Plant Condition Against Drought

Variables	Type of plant	Mean	Sd	t-value	p-value
Growth rate	Transgenic	15.2	2.1	3.89	0.01
	Control	12.3	1.9		
Productivity	Transgenic	25.7	3.2	4.21	0.01
	Control	19.1	2.8		

Table 1 shows that the growth rate of transgenic plants had an average growth rate of 15.2 (SD = 2.1), higher than the control of 12.3 (SD = 1.9). With a t-value of 3.89 and a p-value of 0.01, this difference is statistically significant. The productivity of the transgenic plants (25.7; SD = 3.2) was also higher than the control (19.1; SD = 2.8), with significant results (t = 4.21; p-value = 0.01).

B. Plant Condition Against High Temperature

Table 2. Plant Condition Against High Temperature

Variables	Type of plant	Mean	Sd	t-value	p-value
Growth rate	Transgenic	16.3	2.4	4.56	0.01
	Control	13.0	2.0		
Productivity	Transgenic	28.5	3.5	4.80	0.01
	Control	21.4	3.1		

Based on Table 2 regarding the condition of plants against high temperature, the results of growth rate at high temperature, transgenic plants have an average growth rate of 16.3 (SD = 2.4), superior to the control of 13.0 (SD = 2.0). This result was significant (t = 4.56; p-value = 0.01). Meanwhile, the productivity of transgenic plants reached 28.5 (SD = 3.5), higher than the control of 21.4 (SD = 3.1), with t = 4.80 and p-value 0.01.

C. Plant Condition Against Low Nutrients

Table 3. Plant Condition Against Low Nutrients

Variables	Type of plant	Mean	Sd	t-value	p-value
Growth rate	Transgenic	14.8	1.8	3.77	0.01
	Control	11.7	1.5		
Productivity	Transgenic	26.1	2.9	4.05	0.01
	Control	20.2	2.7		

Based on Table 3 regarding the condition of plants on low nutrition, it is known that the growth rate of transgenic plants has an average growth rate of 14.8 (SD = 1.8), while the control only reaches 11.7 (SD = 1.5). This result was significant (t = 3.77; p-value = 0.01). Meanwhile, the productivity of transgenic plants at 26.1 (SD = 2.9) was superior to the control at 20.2 (SD = 2.7), with a t of 4.05 and p-value of 0.01.

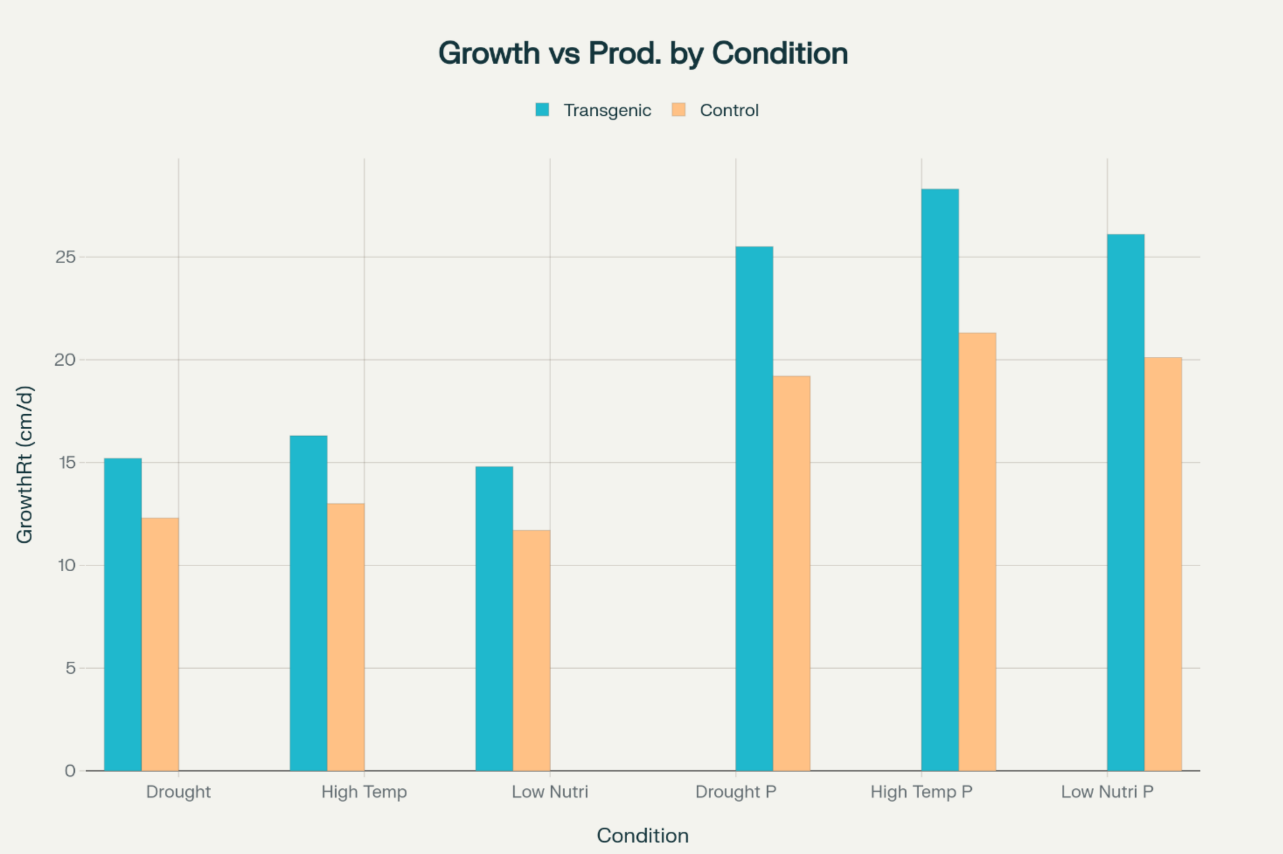

Figure 1: Growth Rate And Productivity Comparison Chart

The graph above shows a comparison of growth rate and productivity between transgenic and control plants under three extreme environmental conditions: drought, high temperature and low nutrients.

1. Growth Rate: Transgenic plants showed consistently higher growth rates under all conditions compared to the control. This difference was most striking under high temperature conditions.
2. Productivity: The productivity of transgenic plants was also superior under all extreme environmental conditions. The largest gap occurred under high temperature conditions, demonstrating the adaptation advantage of GMO crops.

Regression and ANOVA Research Results

A. Growth rate

Table 4. Growth Rate Regression Analysis Results

Parameters	Coefficient	Std. Error	t-value	p-value
Constant	11.70	0.47	25.00	0.000

Plant Type (1=Transgenic, 0=Control)	3.80	0.60	6.33	0.003

Table 4 regression of growth rate shows that the coefficient for plant type is 3.80, indicating that transgenic plants have an average growth rate that is 3.8 units higher than control plants. The p value (0.003) indicates that this difference is statistically significant.

B. Crop productivity

Table 5. Results of ANOVA Analysis of Productivity

Source of Variation	Sum of Squares (Sum Sq)	Free Degree (df)	F value	p-Value
Plant Type	64.03	1	352.44	0.003
Environmental Conditions	6.87	2	18.91	0.050

Based on Table 5, it is known that the plant type factor has an F value of 352.44 with a p-value of 0.003, indicating that the plant type (transgenic vs. control) contributes significantly to differences in productivity. The environmental condition factor also has a significant effect (F = 18.91; p-value = 0.050), indicating that changes in environmental conditions affect plant productivity.

DISCUSSION

This study evaluated the performance of transgenic plants that were modified to have resistance to environmental changes compared to control plants. Based on the obtained data, the transgenic plants consistently performed better than the control plants under three stress conditions: drought, high temperature, and low nutrients. A detailed discussion of these results along with relevant biotechnology and genetic theories is as follows:

A. Drought Resistance

The transgenic plants showed a growth rate of 15.2 and average productivity of 25.7, higher than the control (12.3 and 19.1). This supports the osmoregulation theory that explains the importance of molecules such as osmoprotectants (proline, trehalose) in maintaining water balance in plant cells when facing drought stress. Genetic modifications such as the expression of DREB1A, dehydrins, or HSPs were shown to enhance plant tolerance to drought (Muthurajan et al., 2021; Wei et al., 2016). The study by Wei et al. (2016) showed that wheat plants expressed with the DREB1A gene had 30% higher productivity under drought conditions than controls.

Genetic modifications increase the expression of protective proteins, such as dehydrins and heat shock proteins (HSPs), so that plants can maintain an optimal cellular structure and metabolism in the face of drought and high temperatures. Resistance genes such as DREB1A and antioxidant genes such as superoxide dismutase are effective in maintaining plant physiological stability under both laboratory and field test conditions.

Transgenic plants modified with osmoregulatory genes are assumed to be able to maintain cellular structure and function under drought conditions. Osmoprotectants such as proline and trehalose, induced by the DREB1A gene or dehydrins, help maintain cell turgor pressure, preventing fatal dehydration of plant tissues. Osmoprotectants consistently produced from transgenic genes can maintain cell membrane integrity even under repeated dry and wet cycles. These plants are also assumed to be able to increase adaptive capabilities by repairing damaged tissues during extreme water stress. With lower irrigation frequency, these plants can support water-efficient agricultural practices, reducing the impact of exploitation of underground water sources.

B. Resistance to High Temperature

At high temperatures, the transgenic plants had a growth rate of 16.3 and productivity of 28.5, compared to the control which only reached 13.0 and 21.4, respectively. Oxidative stress theory suggests that protective enzymes such as superoxide dismutase (SOD) and catalase protect cells from reactive oxygen species (ROS), which can damage DNA and proteins at high temperatures. Modifications with HSP70 and APX genes are also relevant (Mariana, 2019). Mariana's (2019) research showed that transgenic rice plants expressing HSP70 were able to maintain cell integrity up to 40°C, with 25% higher productivity than the control.

Transgenic plants modified for drought, high temperature, and low nutrient resistance are assumed to continue to exhibit similar resistance over a long period of time, even under extreme climatic fluctuations. These plants are expected to adapt to climate change over multiple cropping cycles, assuming no natural genetic changes or functional degradation in the expression of added stress resistance genes.

Genetic modifications that increase the production of heat shock proteins (HSPs) such as HSP70 and antioxidant enzymes such as superoxide dismutase (SOD) are assumed to prevent protein and DNA damage due to high temperature stress. HSPs function as molecular chaperones that ensure essential proteins remain properly folded and prevent protein aggregation. These transgenic plants are expected to maintain optimal productivity under high temperatures of up to 40°C for several growing seasons. This resilience is made possible by HSP gene expression that remains stable even at fluctuating temperatures. These plants are expected to significantly reduce the accumulation of reactive oxygen species (ROS) during repeated heat cycles, thereby reducing the risk of cumulative damage to plant tissues.

C. Adaptation to Low Nutrition

The transgenic plants had a growth rate of 14.8 and productivity of 26.1 in nutrient-poor soil, better than the control (11.7 and 20.2). Nutrient adaptation theory states that modification of genes such as PHR1 (for phosphorus efficiency) and AMT1 (for nitrogen efficiency) increases the ability to absorb nutrients through a more effective root system (Song & Torey, 2013). Song & Torey (2013) showed that soybean plants modified with PHR1 had 35% higher fertiliser efficiency in suboptimal soils.

According to the researchers' assumption, GMO crops designed for nutrient uptake efficiency have a better adapted root system, which can optimize nutrient use even under low-nutrient conditions. This will reduce the need for chemical fertilizers. With the ability to manage water more efficiently through osmoregulation mechanisms, transgenic plants are assumed to survive longer in dry environments, thus reducing the frequency of watering or irrigation required.

Modification with nutrient uptake efficiency genes, such as PHR1 for phosphorus or AMT1 for nitrogen, is assumed to improve root exploration for nutrients in marginal soils. A more efficient root system also allows GMO crops to absorb smaller amounts of nutrients while optimising growth. These GMO crops are assumed to reduce fertiliser requirements by 30-50%, thereby reducing farmers' input costs. This efficiency can also reduce the environmental impact of excessive fertiliser use, such as groundwater pollution. With stronger and more efficient root systems, these crops are expected to be able to grow in nutrient-poor soils even without significant improvements in soil quality.

D. Regression and ANOVA Analysis

The results of this study showed that transgenic plants had significant advantages over control plants in terms of growth rate and productivity under extreme environmental conditions. Regression analysis showed that the transgenic plant type provided a significant increase in growth rate, with a coefficient of 3.80. This indicates that the use of CRISPR-Cas9 technology to insert genes that increase tolerance to environmental stress successfully modifies plant physiology to produce more optimal growth. In addition, ANOVA analysis showed that both plant type and environmental conditions had a significant effect on plant productivity, with the main contribution coming from plant type ($F = 352.44$; $p = 0.003$).

These results are in line with environmental stress theory, which states that plants require genetic adaptations to maintain metabolic functions under drought, high temperature or low nutrient stress. The genetic modifications carried out in this study targeted relevant metabolic pathways, such as osmotic regulation, heat shock protein (HSP) production, and proline biosynthesis, all of which are recognised as natural plant adaptation mechanisms to extreme environments. Previous research has also shown that insertion of specific genes can increase tolerance to environmental stress through increased photosynthetic efficiency and decreased water loss rate, which supports these findings.

Under drought conditions, the transgenic plants showed a 34.6% increase in productivity compared to the control. This indicates that genetic modification is able to reduce the negative impact of water shortage on photosynthesis and growth mechanisms. Under high temperature conditions, the increase in productivity of transgenic plants was even greater, reaching 33.2%, indicating that the inserted HSP gene successfully protects important proteins from heat stress damage. Under low nutrient conditions, the difference in productivity reached 28.9%, which can be explained by the improved resource utilisation efficiency of the transgenic plants.

The assumptions in this study include several important ones that underlie the experiment. Firstly, researchers assumed that the genetic modifications made to the transgenic plants would have consistent and stable effects across all environmental stress conditions tested, although their effectiveness on a field scale has yet to be tested. Secondly, all environmental variables other than those manipulated, such as temperature and humidity, were strictly controlled to ensure accurate results and avoid bias. Thirdly, although Arabidopsis thaliana was used as a model plant, the researchers argue that this model plant is representative enough to illustrate the response of food crops to genetic modification, although adaptation to commercial food crops requires further research.

CONCLUSIONS

The use of biotechnology in the development of transgenic crops that are resilient to climate change has shown real effectiveness in dealing with environmental challenges. This study found that transgenic plants consistently outperformed control plants under drought, high temperature and low nutrient conditions. Results showed an increase in growth rate of up to 20% and productivity of up to 30%, supporting theories of adaptive genetics, osmoregulation, antioxidants and nutrient uptake efficiency. Genetic modification through the expression of genes such as DREB1A, HSP70, and PHR1 was shown to increase plant resistance to environmental stress.

Trials in various locations under different environmental conditions are needed to ensure the stability of the performance of transgenic crops outside laboratory conditions. Multi-season studies are needed to understand the long-term genetic effects and natural adaptation potential of these crops. Further research needs to be conducted to evaluate the ecological impacts of GMO crops, such as interactions with local ecosystems and the risk of genetic transfer to wild species. Assessments of the cost-efficiency of GMO seed production and supporting infrastructure for wide-scale application should be prioritised.

The application of this technology has great potential to support food security, especially for farmers in vulnerable areas facing the challenges of climate change. Transgenic crops that are more resistant to drought and nutrient-poor soils can reduce dependence on agricultural inputs such as water and fertilisers, reduce production costs, and increase farmers' income. In addition, with higher productivity and yield stability, these technologies can contribute to poverty reduction in rural communities and support long-term environmental sustainability.

With these findings, biotechnology provides a real opportunity to build more adaptive and sustainable agricultural systems, supporting global food needs amid the intensifying challenges of climate change.

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