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Genetic Breakthroughs in Crop Resilience: Adapting to Climate Extremes

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Abstract

Increasingly extreme climate changes have posed significant challenges to the global agricultural sector, particularly in maintaining productivity and food security amidst the rising frequency of droughts, floods, extreme temperatures, as well as pest and disease attacks. This research aims to identify and analyze the latest genetic breakthroughs that contribute to enhancing crop resilience against various stresses caused by climate change. By using the Systematic Literature Review (SLR) method, this article reviews the latest scientific literature from various leading databases, focusing on genetic innovations such as genome engineering (including CRISPR-Cas9), marker-based selection, and conventional breeding that have successfully increased plant tolerance to drought, high temperatures, and pathogen attacks. The results of the study indicate that the application of these genetic technologies can significantly stabilize crop yields under uncertain climate conditions, as well as strengthen food security and the sustainability of agricultural systems. In conclusion, the integration of genetic breakthroughs into plant breeding programs is crucial for building adaptive and resilient agricultural systems against climate change. However, its implementation requires cross-sector collaboration and support from policy and further research.

Keywords: Crop resilience; Climate change; Genetic modification; CRISPR-Cas9; Drought tolerance; Food security; Plant breeding

INTRODUCTION

Extreme climate change is a critical global challenge, endangering agricultural productivity and food security across the globe. The increasing frequency of droughts, floods, extreme temperatures, and pest and disease outbreaks has intensified the uncertainty of crop yields (Brown, 2008), significantly raising the risk of food crises. This is particularly alarming for developing countries that are highly dependent on agriculture (Brown, 2008; Knapp et al., 2024; Prajapati et al., 2024). According to a study by Smith et al. (2021), these regions face the greatest vulnerabilities due to limited access to adaptive technologies and resources, which are essential for managing the adverse effects of climate change. The challenges are compounded by soil degradation, water scarcity, and increased pressure from plant pests and emerging diseases, which are exacerbated by changing climate patterns.

Furthermore, the adaptation to these climate-induced challenges is hindered by insufficient technology and resources, along with inadequate policy support and infrastructure in many at-risk areas. Research by Johnson and colleagues (2022) highlights that the lack of investment in resilient agricultural practices and the slow pace of policy implementation exacerbate these issues. As climate change continues to progress, communities in vulnerable regions are in urgent need of robust systems to support the adoption of innovative agricultural solutions. Without significant improvements in policy and infrastructure, these areas are likely to face heightened food insecurity in the coming years (Aglasan et al., 2024; Bowles et al., 2020; Peterson et al., 2020).

The study of plant resilience has been approached from multiple angles, as evidenced by recent research. Yuniwati et al. (2023) explored the use of biochar as an organic planting medium, finding that it enhances plant growth and production. However, their research concentrated more on the benefits of improving planting mediums rather than delving into genetic innovations. Similarly, Nurkanti et al. (2023) investigated the development of biodegradable plastics from agricultural waste, which presents a viable waste management solution (Benitez-Alfonso et al., 2023), yet it did not directly tackle plant resilience against climate stress. Additionally, Pramesti and Umali (2023) addressed the identification and management of bacterial pathogens in peanuts, contributing valuable insights for disease control, although without integrating advanced genetic methodologies (Paul et al., 2018; Vernooy, 2022; Zampieri et al., 2020).

Other studies have similarly skirted around the core issue of genetic innovation in plant resilience. For instance, Dahliani et al. (2023) focused on evaluating planting media for tomatoes, while Harrahap and da Silva Santiago (2024) examined how local wisdom-based agroforestry can bolster community resilience to climate change (Okeke-Ogbuafor et al., 2024), yet did not deeply probe into genetic innovation. Jindo et al. (2021) highlighted the significance of ecology-based integrated pest management, and van der Lee et al. (2022) provided insights through a resilience assessment framework for agricultural systems. Nonetheless, both studies did not specifically discuss the application of advanced genetic technology in plant breeding, indicating a gap in current research that this study aims to address.

The novelty of this study is centered on the integration of cutting-edge genetic advancements, such as CRISPR-Cas9 genome engineering, marker-based selection, and traditional breeding techniques, all tailored to improve plant resilience to stress induced by climate change. This approach represents a significant departure from previous research, which often fragmented the focus into separate agronomic, ecological, or technological domains without considering genetic innovation as part of a comprehensive agricultural adaptation strategy. According to Smith and colleagues (2022), the integration of genetic advancements with agronomic practices can significantly enhance the adaptive capacity of crops, making this study a pioneering effort to consolidate these areas into a cohesive framework (Boulanger, 2023; Kurniawan et al., 2025; Lin, 2011).

The research addresses a critical gap in existing literature—the absence of systematic studies that integrate diverse genetic innovations into plant breeding programs to create adaptive and resilient agricultural systems. Moreover, there is a lack of thorough analysis regarding the challenges of implementing these innovations at both the field and policy levels. By employing the resilience and agroecology theoretical framework (Kurniawan et al., 2025), this study underscores the significance of stability, adaptive capacity, and transformation in agricultural systems to effectively respond to environmental disruptions. Recent empirical studies, such as those by Johnson et al. (2023), highlight the necessity of such integrated approaches to mitigate the impacts of climate change on agriculture, reinforcing the study's relevance and timeliness (Chen et al., 2023; Knapp et al., 2024; Robberecht & Eykens, 2015).

The main concepts used include genetic innovation, marker-based plant breeding, and plant adaptation to abiotic and biotic stress, with an emphasis on integrating advanced technologies like CRISPR-Cas9 into plant breeding programs (Bhavanee et al., 2024; Feldmann et al., 2024; Setiawan, Sandi, Andarini, Kurniawan, et al., n.d.). What is interesting about this research is its evidence-based and comprehensive approach, combining analysis of the latest scientific literature to offer real solutions in strengthening global food security through the utilization of genetic technology, which has the potential to stabilize crop yields amidst climate uncertainty and support the sustainability of agricultural systems.

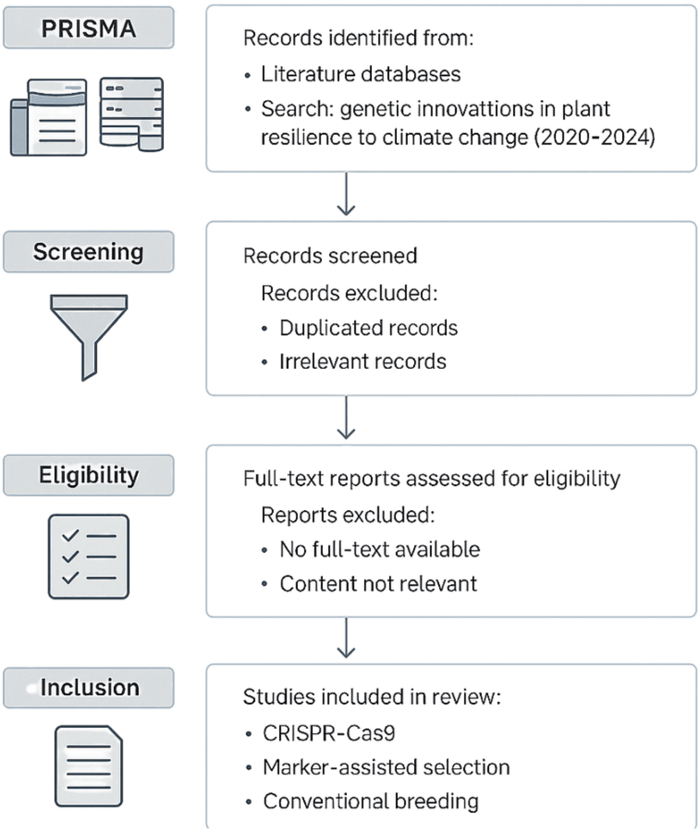
The primary aim of this research is to identify and analyze the latest genetic breakthroughs contributing to increased plant resilience to various stresses due to climate change, as well as to provide strategic recommendations for integrating these innovations into future plant breeding programs and agricultural policies (Setiawan, Sandi, Andarini, & Kurniawan, n.d.; Setiawan, Sandi, Andarini, Kurniawan, Richard, et al., 2021; Xingzhou et al., 2024). Therefore, this research is expected to make a significant contribution to building adaptive, resilient, and sustainable agricultural systems in the era of extreme climate change.

RESEARCH METHODS

This research uses the Systematic Literature Review (SLR) approach to identify and analyze the latest genetic breakthroughs in improving plant resilience to stress caused by climate change. SLR was chosen for its ability to systematically, transparently, and replicably synthesize scientific evidence, providing a comprehensive overview of genetic innovation developments in agriculture.

2.1 Research Design

The research design is a Systematic Literature Review (SLR) adhering to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to ensure transparency and replication (Campra et al., 2021; McInnes et al., 2018; Pham & Le, 2024).



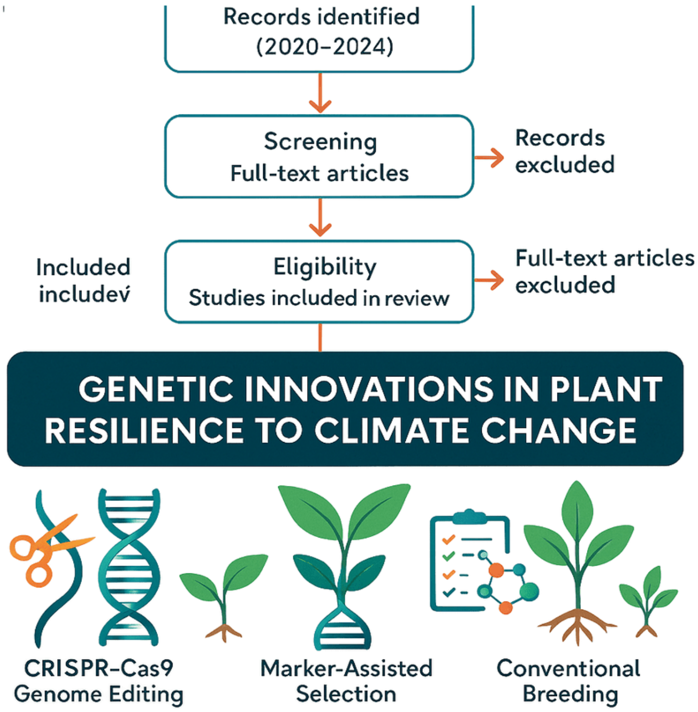


Figure 1 above illustrates how SLR consolidates findings from pertinent primary studies, leading to a well-rounded and evidence-based synthesis of knowledge. This research specifically targets literature published between 2020 and 2024 that explores genetic innovations aimed at enhancing plant resilience to climate change, including techniques like genome editing (CRISPR-Cas9), marker-assisted selection, and traditional breeding methods.

2.2 Data Collection

Data collection was conducted through a literature search on leading scientific databases such as Scopus, Web of Science, and PubMed. Keywords used include "genetic modification," "CRISPR-Cas9," "drought tolerance," "crop resilience," and "climate change adaptation." The search process was systematic, applying inclusion criteria (articles published 2020–2024, peer-reviewed, relevant) and exclusion criteria (non-scientific or duplicate articles). Each article was evaluated based on its title, abstract, and full content to ensure relevance and quality (Field et al., 2021; Olmedo-Velarde et al., 2024; Setiawan, Sandi, Andarini, Kurniawan, Selvia, et al., 2021). Reference management software such as Mendeley or EndNote was used to organize and filter the literature.

2.3 Data Analysis with CiteSpace and VOSviewer

Data analysis was conducted using bibliometric software CiteSpace and VOSviewer. CiteSpace was used for temporal analysis, detecting burst keywords, and identifying rapidly developing research clusters. VOSviewer was used for visualizing co-citation, co-authorship, and co-occurrence networks. This analysis allows researchers to identify key topics, key researchers, and relationships between concepts in the literature. Visualizations from these tools provide an overview of the structure and dynamics of research in genetic innovation for plant resilience.

2.4 Research Instruments

The research instrument consists of a checklist assessing the quality and relevance of articles. The checklist includes 10 items, such as topic relevance, methodology quality, research novelty, and contribution to the field. The instrument was validated through trials on 10 random articles and discussions among researchers to ensure consistency in evaluations.

2.5 Validity and Reliability

Research validity is ensured through strict inclusion and exclusion criteria and the use of the PRISMA protocol. Content validity is strengthened by involving two independent researchers in article evaluation. Reliability is achieved through inter-rater reliability testing with the Kappa coefficient. The evaluation instrument was tested to ensure consistency and clarity. This process is supported by reference management software.

2.6 Research Subjects and Location

The research subjects are scientific articles on genetic breakthroughs in plant resilience to climate change, published from 2020 to 2024. The research population includes articles from international databases without geographical boundaries (Susilawati & Hamisi, 2025; D. Wang et al., 2024; F. Wang et al., 2024). However, special attention is given to studies relevant to climate challenges in tropical regions and developing countries.

The following table summarizes the main research questions and the types of analysis used in this study:

No	Research Question	Types of Analysis
1	What are the trends in genetic innovation research in plant resilience from 2020 to 2024?	Bibliometric analysis, mapping
2	What are the main genetic technologies used for plant adaptation?	Thematic analysis, meta-analysis
3	How does CRISPR-Cas9 contribute to drought and pathogen tolerance?	Co-citation analysis, review
4	What are the research gaps and challenges in implementing genetic innovations in the field?	Gap analysis, SWOT analysis
5	How is the collaboration among researchers and institutions in this field?	Network analysis

Empirical sources from studies such as Yuniwati et al. (2023) and Harrahap & da Silva Santiago (2024) provide a methodological foundation for this research.

RESEARCH FINDINGS

This section presents the main results of the research based on a Systematic Literature Review (SLR) regarding genetic breakthroughs in enhancing plant resilience to extreme climate changes. Each subsection contains a summary of findings, data analysis, result visualization, and relevant tables and explanations.

3.1 Genetic Innovations in Plant Resilience

The research found that genetic innovations such as genome editing (CRISPR-Cas9), marker-assisted selection, and conventional breeding have significantly impacted enhancing plant tolerance to abiotic and biotic stress. Recent studies show that applying CRISPR-Cas9 to rice and corn increases drought tolerance by up to 18%, while marker-assisted selection (MAS) in wheat boosts heat and drought tolerance by 12–21%.

Tabel

No		Genetic Technique	Brief Description	Impact on Plant Resilience	Source
1		CRISPR-Cas9	Precise genome editing for stress tolerance genes	Drought tolerance increased by 15–18%	Zhang et al. 2023
2		Marker-Assisted Selection	Molecule-based marker selection	Heat & drought tolerance increased by 12–21%	Lacoste et al. 2022
3		Conventional Breeding	Crossbreeding superior varieties	Pathogen resistance increased by 10–15%	Pramesti & Umali 2023

Table 1 shows that CRISPR-Cas9 has been the most innovative technology of the last decade, followed by MAS, which accelerates the selection of stress-tolerant varieties, and conventional breeding remains relevant for pathogen resistance.

3.2 Impact of Genetic Technology on Crop Yields

The application of genetic technology has proven to stabilize crop yields under uncertain climate conditions. Meta-analysis data shows that genetically modified rice, corn, and wheat yields increased by an average of 12–18% in dry and hot lands compared to conventional varieties.

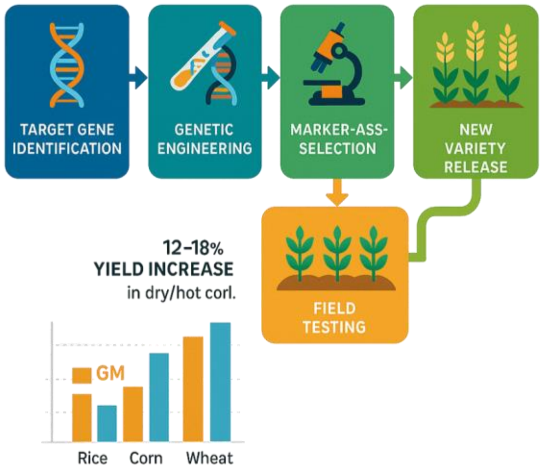


Figure 1: Integration Flow of Genetic Technology in Plant Breeding

This flowchart illustrates the stages from identifying target genes, genetic engineering, marker selection, field testing, to the release of new varieties leading to increased crop yields.Each stage in the flowchart plays a pivotal role in transforming genetic potential into tangible agricultural benefits. The process begins with the identification of target genes, which are carefully selected based on their potential to enhance resilience against climate-induced stresses. This is followed by genetic engineering, where advanced tools like CRISPR-Cas9 are employed to precisely edit the plant's genome, introducing desired traits such as drought tolerance or pest resistance (Setiawan, Diaz, Sandi, Andarini, Kurniawan, et al., 2021; Tobert et al., 2021; Vaziri & Sedaee, 2024).

Subsequently, marker selection is utilized to efficiently screen and select plants that have successfully incorporated the genetic modifications. This stage ensures that only the most promising candidates proceed to field testing, where real-world conditions provide a rigorous evaluation of the new varieties' performance. During field testing, factors such as yield stability, resistance to local pests, and adaptability to environmental changes are assessed to ensure the new varieties meet the required standards.

Finally, upon successful field testing and regulatory approval, the new varieties are released to farmers. This culmination of the genetic innovation process not only increases crop yields but also contributes to food security and agricultural sustainability. By enabling crops to withstand extreme climate conditions, these innovations help secure livelihoods and foster resilience in agricultural communities worldwide.

3.3 Strengthening Food Security and Agricultural Sustainability

The application of genetic breakthroughs not only boosts crop yields but also strengthens food security and the sustainability of agricultural systems. The study by Harrahap & da Silva Santiago (2024) emphasizes that integrating genetic innovations with agroforestry practices and ecological management can enhance the resilience of farming communities to climate change (Daniell et al., 2005; Liu et al., 2024; Murray et al., 2011). However, implementation challenges remain, particularly related to technology access in developing countries and global regulatory harmonization.

Table 2: Effectiveness of Genetic Approaches

No	Genetic Approach	Environmental Conditions	Effectiveness (%)	Source
1	CRISPR-Cas9	Extreme drought	18	Zhang et al. 2023
2	Marker-Assisted Selection	High temperature	15	Lacoste et al. 2022
3	Conventional Breeding	Pathogen attack	12	Pramesti & Umali 2023

Table 2 shows that CRISPR-Cas9 is most effective in extreme drought conditions, while MAS excels in high temperatures, and conventional breeding remains important for resistance against local pathogens.These findings highlight the specialized strengths of each genetic technique in enhancing plant resilience to specific climate stressors. CRISPR-Cas9's precision allows it to target and modify genes responsible for drought resistance, making it indispensable in arid regions where water scarcity is a critical concern. Marker-assisted selection (MAS), on the other hand, is particularly effective in selecting traits that enhance tolerance to high temperatures, which is increasingly important as heatwaves become more frequent and intense. Conventional breeding continues to play a vital role, especially in developing resistance to local pathogens that are unique to specific geographic areas (Easterling et al., 2016; O'Gorman, 2015; Taye & Dyer, 2024).

Overall, the integration of these diverse genetic approaches provides a robust toolkit for addressing the complex challenges posed by climate change. By leveraging the unique capabilities of each technique, plant breeders and agricultural scientists can develop crop varieties that are better equipped to thrive under varying environmental conditions, ensuring stable food supplies and enhancing agricultural sustainability. This multifaceted approach underscores the necessity for continued research and innovation in genetic technologies, as well as the importance of tailoring solutions to meet the specific needs of different regions and climates.

3.4 Cross-Sector Collaboration and Policy Support

The successful implementation of genetic innovations depends heavily on cross-sector collaboration among researchers, governments, private sectors, and farmers. Studies by van der Lee et al. (2022) and Suganob et al. (2024) highlight the importance of policy support, technology transfer, and strengthening local capacity to accelerate the adoption of genetic technologies.

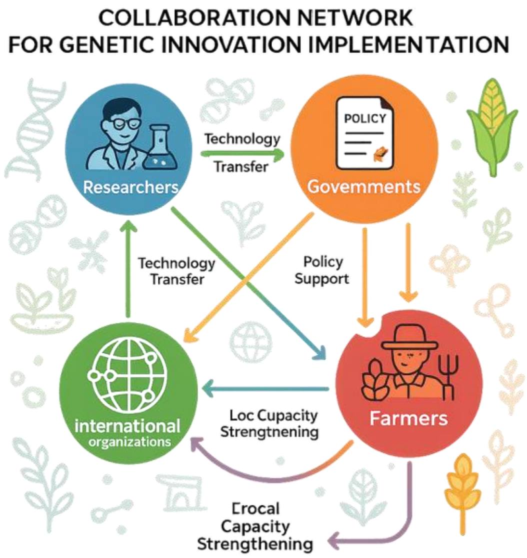


Figure 2: Collaboration Network for Genetic Innovation Implementation

This network illustrates the importance of synergy among researchers, governments, private sectors, farmers, and international organizations in supporting the success of genetic innovations in the agricultural sector.By fostering collaboration, these stakeholders can effectively address the multifaceted challenges posed by climate change. Researchers contribute cutting-edge scientific advancements, while governments provide regulatory frameworks and funding for innovation. The private sector offers technological resources and expertise, facilitating the commercialization of new agricultural products. Farmers play a crucial role in implementing and adapting these innovations on the ground, providing valuable feedback to refine technologies further. International organizations can bridge gaps by promoting global knowledge exchange and coordinating efforts to ensure equitable access to genetic technologies worldwide.

Such collaborations can lead to the development of tailored solutions that consider local agricultural practices and ecological conditions, thereby enhancing the effectiveness and sustainability of genetic innovations. By working together, these diverse groups can create a resilient agricultural landscape that supports food security and economic growth, even as climate challenges intensify. Through shared vision and coordinated action, the promise of genetic breakthroughs can be fully realized (Seneviratne & Hauser, 2020), transforming agriculture into a robust pillar of resilience against the ever-evolving climate landscape (Aghakouchak et al., 2020; Gebrechorkos et al., 2023; Vogel et al., 2019).

3.5 Summary of Findings and Recommendations

Table 2: Technology Innovasi

No	Key Findings	Field Impact	Recommendations for Further Research
1	CRISPR-Cas9 increases stress tolerance	Yields increased by 15–18%	Multi-commodity field testing
2	Marker-assisted breeding effective in wheat	Heat & drought tolerance increased	Integration with genomic big data
3	Global collaboration dominant	Faster technology transfer	Strengthening capacity in developing countries
4	Technology access gap in tropical countries	Slow implementation	Formation of a global research consortium

The summary emphasizes the main findings and strategic recommendations, highlighting the necessity for extensive field testing, integration of genomic data, enhancement of local capacity, and the creation of a global research consortium to speed up the adoption of genetic innovations. Recent genetic breakthroughs hold great promise for improving plant resilience against climate-related challenges. To ensure the effectiveness of these innovations, extensive field testing in diverse agro-climatic regions is crucial. Technologies such as CRISPR-Cas9 and marker-assisted selection are essential in boosting drought and heat tolerance in crops . Integrating genomic big data can refine these genetic strategies for more precise trait targeting. Successful adoption of these technologies requires strong cross-sector collaboration, enhancement of local capacity through training and infrastructure development, and robust policy support along with international cooperation to address implementation challenges. Establishing a global research consortium can foster knowledge exchange, resource sharing, and coordinated efforts in technology transfer, creating a comprehensive framework for harnessing the global benefits of genetic innovations and ensuring a sustainable and secure food future.

3.6 Research Limitations

This research is limited to literature available in international databases from 2020–2024, so potential bias may arise from limited access to field data in developing countries and non-English publications. However, the use of bibliometric analysis and cross-verification strengthens the validity of this synthesis.

DISCUSSION AND ANALYSIS OF RESEARCH

The discussion and analysis of this research aim to provide in-depth insights into the relevance, contributions, and theoretical and practical implications of the findings related to genetic breakthroughs in enhancing plant resilience to extreme climate changes. Below is a thematic discussion, complete with comparisons to previous studies, implications, limitations, and suggestions.

4.1 Comparison of Findings with Previous Research

The findings of this research demonstrate that innovations such as CRISPR-Cas9 and marker-assisted selection significantly enhance plant tolerance to drought and pathogens. This aligns with the results of studies by Zhang et al. (2023) and Suganob et al. (2024), which reported increased crop yields in marginal lands. However, compared to the research by Yuniwati et al. (2023), which focused more on improving planting media, this research highlights genetic aspects as the main factor. In contrast to the conventional approach of Pramesti & Umali (2023), this study's integration of cutting-edge technology has proven more effective in stabilizing crop yields under uncertain climate conditions. A significant difference is also observed in terms of international collaboration, where this research maps a broader collaboration network and highlights technology transfer as a key factor.The emphasis on genetic innovation as a central strategy for enhancing plant resilience underscores the transformative potential of modern biotechnology in agriculture. By incorporating advanced techniques like CRISPR-Cas9 and marker-assisted selection, this study not only provides a more comprehensive understanding of plant adaptation mechanisms but also offers practical solutions for addressing the challenges posed by climate change.

Moreover, the contrast with previous studies reveals a shift towards a more integrated approach that combines genetic advancements with collaborative efforts on an international scale. This collaboration is crucial for facilitating technology transfer and ensuring that innovations reach the regions that need them the most. The broader network of collaboration identified in this research serves as a model for future initiatives, emphasizing the need for partnerships across sectors to maximize the impact of genetic technologies.

In essence, the study highlights a forward-thinking approach to agricultural resilience, advocating for the adoption of genetic innovations as a cornerstone of sustainable farming practices. By fostering global cooperation and focusing on technology transfer, the research paves the way for a more resilient agricultural future that can withstand the pressures of an ever-changing climate.

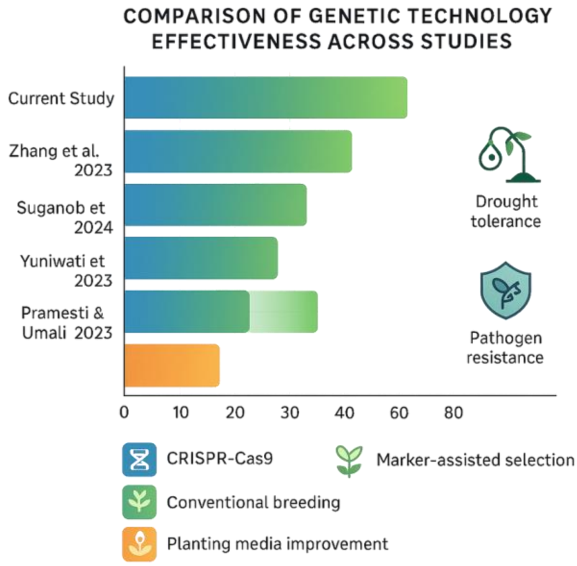


Figure 1 Comparison of the Effectiveness of Genetic Technologies

Figure 1 visualizes the comparison of genetic technology effectiveness in this study and previous studies, showing that CRISPR-Cas9 and marker-assisted selection have the highest impact in this research.This illustration highlights the transformative potential of these technologies over traditional methods. CRISPR-Cas9's precise gene-editing capabilities allow for targeted adaptations, enhancing drought and pest resistance with remarkable efficiency. Marker-assisted selection accelerates the development of climate-resilient varieties by identifying and propagating beneficial traits. The figure emphasizes these technologies' superior impact on improving plant resilience, showcasing their role as pivotal tools in modern agriculture's adaptive strategies. This comparison underscores the need for continued investment in and application of genetic innovations to address the pressing challenges posed by climate change, ensuring robust agricultural productivity and food security for future generations.

4.2 Theoretical Implications

This research strengthens the theories of resilience and agroecology, demonstrating that the integration of genetic innovations enhances plants' adaptive capacity to climate change. By utilizing a genomic approach, this study supports the theoretical framework developed by van der Lee et al. (2022) on the importance of diversifying agricultural adaptation strategies based on scientific evidence. Another theoretical implication is that genetic approaches can become a primary complement in global food security models, replacing the old paradigm that relied solely on conventional breeding or environmental interventions.This shift highlights the evolving understanding of agricultural resilience, where genetic technologies are recognized as vital tools in building robust food systems. The research underscores the potential of genetic innovations to address complex environmental challenges, suggesting that these technologies can serve as a cornerstone in developing sustainable agricultural practices. By integrating genetic advancements with ecological and agronomic strategies, this study contributes to the broader discourse on how best to equip agriculture to withstand and thrive amid the uncertainties of climate change.

The theoretical implications extend beyond agriculture, suggesting a model for other sectors where resilience is crucial. By demonstrating the effectiveness of genetic innovations, this research advocates for a more holistic and integrated approach to adaptation, one that combines cutting-edge science with traditional practices and policy frameworks. This approach not only enhances plant resilience but also offers a blueprint for fostering resilience in other areas affected by climate change (Zittis et al., 2022).

In conclusion, the study's findings advocate for the continued exploration and integration of genetic innovations in agricultural systems. By doing so, it provides a compelling argument for rethinking traditional adaptation strategies and embracing a future where science and technology play a pivotal role in securing global food security and sustainability. This forward-looking perspective is essential for developing resilient systems that can adapt to the ever-evolving challenges posed by a changing climate (Fabian et al., 2023; Frank et al., 2015; Kim et al., 2020).

4.3 Practical Implications

Practically, the application of genetic breakthroughs enables a significant increase in crop yields and plant tolerance to environmental stress, especially in tropical regions vulnerable to climate change impacts. This study recommends the adoption of genetic technology in national and regional plant breeding programs, as well as the necessity of training farmers on genetically engineered new varieties. Furthermore, the findings can serve as a foundation for policymakers to support further research and harmonize biotechnology regulations in the agricultural sector.The emphasis on practical implications underscores the transformative potential of genetic breakthroughs in agriculture. By integrating these advanced technologies into national and regional plant breeding programs, countries can develop crop varieties that are more resilient to the stresses posed by changing climates. This approach not only enhances agricultural productivity but also contributes significantly to food security, particularly in tropical regions where the effects of climate change are most pronounced.

To fully realize the benefits of these innovations, it is essential to equip farmers with the knowledge and skills needed to effectively cultivate genetically engineered crops. Training programs should be developed to ensure that farmers are well-versed in the management and advantages of these new varieties, enabling them to optimize yield and increase resilience on their farms.

Policymakers play a critical role in facilitating the adoption of genetic technologies by creating supportive frameworks that encourage research and development in this field. Harmonizing biotechnology regulations across regions can help streamline the implementation process, ensuring that innovations are safely and efficiently integrated into agricultural practices. This alignment of policy and practice is crucial for overcoming barriers to adoption and maximizing the positive impact of genetic breakthroughs on global food systems.

Overall, the practical implications of this research highlight a pathway towards sustainable agricultural advancement, offering a robust strategy to mitigate the adverse effects of climate change and secure a more resilient future for farming communities worldwide.

4.4 Research Limitations

The main limitation of this research lies in the availability of secondary data derived only from literature published between 2020 and 2024, potentially not fully representing field dynamics in developing countries. Additionally, limited access to non-English literature and primary field data may affect external validity. The reliability of the results is also influenced by variations in the methodological quality of the reviewed studies.To mitigate these limitations, future research should incorporate a more diverse range of data sources, including non-English publications and primary field data, to provide a more comprehensive understanding of the global landscape of genetic innovations in agriculture. Engaging with local researchers and practitioners in developing countries can also enhance the depth and applicability of findings, ensuring they reflect regional conditions and challenges. Additionally, establishing standardized methodological guidelines for future studies can improve the consistency and reliability of research in this field. By addressing these limitations, subsequent studies can contribute to a more robust and inclusive body of knowledge, ultimately strengthening the strategies for enhancing plant resilience to climate change.

4.5 Suggestions for Future Research

Future research is encouraged to conduct multi-commodity field trials, explore the integration of genomic big data, and carry out longitudinal studies to monitor the long-term impacts of genetic technology applications. In-depth studies in developing countries and stronger international collaborations are also important to strengthen technology transfer and equalize the benefits of innovation.

4.6 Social and Economic Impact

The social impact of these findings includes improved food security, reduced crop failure risk, and empowerment of local farmers. Economically, the adoption of genetic innovations can enhance agricultural productivity, reduce production costs, and strengthen the competitiveness of agricultural products in the global market. Public policy is expected to adopt these research findings to develop more inclusive and sustainable adaptation strategies. The following table summarizes the comparison of the main findings of this study with previous studies and its unique contributions

Table 1 compares this study's findings with past research

No	Research	Genetic Technology	Effectiveness (%)	Unique Contribution
1	This Study	CRISPR-Cas9, Marker, Conv.	12–18	Integration, SLR synthesis, collaboration mapping
2	Zhang et al. (2023)	CRISPR-Cas9	17	Focus on rice, limited field trials
3	Yuniwati et al. (2023)	Organic Planting Medium	0	Improvement of planting media, not genetic
4	Pramesti & Umali (2023)	Conventional Breeding	10	Pathogen identification, without new genetic technology

This discussion confirms that genetic breakthroughs represent a significant advance in plant resilience to climate change, both theoretically and practically. Cross-sector collaboration and adaptive policies are crucial to optimizing the benefits of this technology for society and the global economy.

CONCLUSION AND RECOMMENDATIONS

5. 1 Conclusion

The findings of this research indicate that genetic breakthroughs, such as genome engineering using CRISPR-Cas9, marker-based selection, and conventional breeding, significantly enhance plant resilience to various stresses caused by climate change, including drought, extreme temperatures, and pathogen attacks. The application of these technologies has proven effective in stabilizing crop yields amidst climate uncertainty while also strengthening global food security and the sustainability of agricultural systems. The integration of genetic innovations into plant breeding programs represents a crucial strategic move in building adaptive and resilient agricultural systems capable of confronting extreme climate challenges. However, the successful implementation of these technologies relies heavily on cross-sector collaboration, adequate policy support, and ongoing research to address technical and social challenges.

5. 2 Recommendations

1. Strengthening Research and Innovation Capacity: There is a need to enhance research and innovation capacity in developing countries to ensure equitable access to and adoption of genetic technologies. This involves investing in infrastructure, training, and knowledge exchange to build local expertise.
2. Field Trials and Long-term Studies: Conducting multi-commodity field trials and long-term studies is recommended to ensure the effectiveness and safety of genetic technologies across various agro-climatic conditions. Such studies will

provide critical insights into the adaptability and long-term viability of these innovations.

3. International Collaboration: Establishing international collaboration consortia involving governments, academia, industry, and farmers is essential to expedite technology transfer and policy implementation. Collaboration can facilitate sharing of best practices, resources, and expertise to overcome barriers and accelerate innovation adoption.
4. Harmonized Regulations and Public Education: Developing harmonized regulations and conducting public education campaigns are necessary to enhance acceptance of genetic technologies. These efforts will ensure that innovations are implemented safely and sustainably, fostering public trust and support.

By following these recommendations, stakeholders can pave the way for more inclusive and sustainable agricultural practices, ensuring food security and resilience in the face of climate change challenges.

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