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CRISPR-BASED CROP ENHANCEMENT FOR CLIMATE-RESILIENT WHEAT PRODUCTION IN PAKISTAN

Muhmmad Waqas[*1], Pir Arshad Ahmed Jan Sirhandi[2]

[*1]Department of Biotechnology university of Agriculture Peshawar
[2]*PhD scholar Botany, University of Sindh Jamshoro, Assistant professor, Govt boys Degree College Tando Muhammad Khan*

[2]sirhandijan79@gmail.com

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Corresponding Author: *
Muhmmad Waqas

Abstract

Climate change has emerged as a major threat to sustainable wheat production in Pakistan due to increasing temperatures, drought, salinity, water scarcity, and climate-induced plant diseases. Conventional wheat breeding approaches are often insufficient to address rapidly evolving environmental stresses, thereby creating the need for advanced and precise crop improvement technologies. This study examined the potential of CRISPR-based genome-editing technology for enhancing climate-resilient wheat production in Pakistan. The research adopted a quantitative and explanatory research design using a cross-sectional survey approach. Data were collected from 300 respondents, including agricultural researchers, wheat breeders, extension officers, policymakers, and progressive farmers from major wheat-producing regions of Pakistan. Statistical analysis was conducted using SPSS, including descriptive statistics, correlation analysis, and multiple regression analysis. The findings revealed that CRISPR/Cas genom

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most strategically important cereal crops worldwide and serves as a primary staple food for more than 35% of the global population. In Pakistan, wheat contributes significantly to national food security, rural livelihoods, and the agricultural economy. The crop occupies the largest cultivated area in the country and constitutes a major source of caloric intake for the population. However, wheat productivity in Pakistan is increasingly threatened by climate change–induced stresses, including rising temperatures, prolonged droughts, erratic rainfall patterns, soil salinity, and the emergence of new pests and diseases. These environmental challenges have substantially reduced crop productivity, grain quality, and resource-use efficiency, thereby threatening sustainable agricultural development and national food security (Choudry et al., 2024; Kaur et al., 2025). Pakistan is recognized among the countries highly vulnerable to climate variability due to its arid and semi-arid agroecological conditions.

Heat stress during the reproductive and grain-filling stages of wheat significantly decreases yield potential, while water scarcity and salinity further aggravate crop losses. Conventional breeding approaches have contributed to wheat improvement over the decades; however, these methods are often time-consuming, labor-intensive, and insufficient to cope with rapidly evolving climatic conditions. The growing demand for climate-resilient crop varieties necessitates the adoption of advanced biotechnological interventions capable of accelerating precision breeding and enhancing stress tolerance in wheat (Chen et al., 2024; Kaur et al., 2025).
Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)-associated protein systems, commonly known as CRISPR/Cas technology, have emerged as

revolutionary genome-editing tools for modern agriculture. CRISPR/Cas systems enable precise, efficient, and targeted modification of plant genomes without introducing undesirable genetic changes. Compared with traditional genetic engineering techniques, CRISPR technology offers higher specificity, reduced breeding time, cost-effectiveness, and the ability to simultaneously edit multiple genes associated with important agronomic traits (Ali et al., 2024; Chen et al., 2024). The technology has been successfully applied in several staple crops to improve tolerance against abiotic stresses such as drought, salinity, heat, and oxidative stress, as well as resistance to pathogens and insect pests.

Recent advances in CRISPR-based genome editing have demonstrated substantial potential for enhancing climate resilience in wheat. Researchers have identified and edited stress-responsive genes involved in heat tolerance, osmotic regulation, root architecture, water-use efficiency, and disease resistance. The development of multiplex genome-editing strategies further enables simultaneous improvement of multiple traits, thereby supporting the production of high-yielding and climate-smart wheat cultivars (Plant Science, 2024). Additionally, innovations such as base editing, prime editing, and CRISPR activation/repression systems have expanded the scope of precision crop improvement and functional genomics in cereals (Li et al., 2024).

The application of CRISPR technology is particularly relevant for Pakistan, where increasing climatic instability continues to threaten wheat productivity. The country faces severe challenges related to water scarcity, increasing soil salinization, and temperature extremes, all of which negatively affect crop growth and yield stability. Integrating CRISPR-mediated genome editing into wheat breeding programs can facilitate the rapid development of resilient cultivars capable of adapting to harsh environmental conditions while maintaining high productivity and nutritional quality. Furthermore, CRISPR-based breeding can support sustainable agriculture by reducing dependence on chemical inputs, improving nutrient-use efficiency, and minimizing environmental degradation (Ngongolo & Mmbando, 2024).

Despite its enormous potential, the implementation of CRISPR technology in Pakistan's agricultural sector remains limited due to regulatory uncertainties, inadequate research infrastructure, biosafety concerns, and limited technical expertise. Addressing these challenges requires strong institutional collaboration, investment in biotechnology research, and the development of science-based regulatory frameworks to facilitate responsible genome-editing applications in crop improvement. Strengthening public awareness and policy support is equally essential to promote the adoption of genome-edited crops for sustainable food production.

Therefore, CRISPR-based crop enhancement represents a promising and transformative strategy for developing climate-resilient wheat varieties in Pakistan. By enabling precise genetic modifications associated with stress tolerance, yield stability, and resource-use efficiency, CRISPR technology has the potential to revolutionize wheat breeding and contribute significantly to national food security under changing climatic conditions. Continued research, technological advancement, and policy integration will be critical for harnessing the full potential of genome editing in Pakistan's agricultural system.

Problem Statement

Climate change has emerged as one of the most critical threats to global agricultural sustainability, particularly in developing countries where food systems are highly vulnerable to environmental instability. Pakistan, being an agrarian economy, relies heavily on wheat production as a major source of food security, rural income, and economic stability. Wheat contributes substantially to the daily caloric intake of the Pakistani population and occupies the largest cultivated agricultural area in the country. However, the productivity and sustainability of wheat cultivation are increasingly threatened by rising temperatures, erratic rainfall, prolonged droughts, soil salinity, water scarcity, and the emergence of climate-induced pests and diseases. These environmental stresses significantly reduce wheat yield, grain quality, and resource-use efficiency, thereby intensifying the risk of food insecurity and economic instability.

Traditional wheat breeding techniques have historically contributed to crop improvement; nevertheless, these methods are relatively slow, labor-intensive, and less effective in addressing rapidly evolving climatic challenges. The complexity of wheat genetics, combined with the urgent need for stress-tolerant and high-yielding cultivars, requires innovative and precise breeding technologies capable of accelerating crop improvement. In recent years, CRISPR/Cas genome-editing technology has gained considerable global attention due to its ability to precisely modify target genes associated with agronomic and stress-responsive traits. The technology provides opportunities to develop climate-resilient wheat varieties with enhanced tolerance to drought, heat, salinity, and diseases while maintaining productivity and nutritional quality.

Despite the promising potential of CRISPR-based genome editing, its practical application in Pakistan's wheat breeding programs remains limited. The country faces multiple challenges, including insufficient biotechnology infrastructure, limited technical expertise, weak collaboration between research institutions, inadequate funding, biosafety concerns, and unclear regulatory frameworks governing genome-edited crops. Furthermore, there is limited empirical research focusing specifically on the role of CRISPR technology in developing climate-resilient wheat varieties suitable for Pakistan's agroecological conditions. The absence of comprehensive scientific and policy-oriented studies restricts the integration of genome-editing technologies into national agricultural development strategies.

Therefore, there is a critical need to explore the potential of CRISPR-based crop enhancement for improving wheat resilience under changing climatic conditions in Pakistan. This study seeks to investigate how CRISPR genome-editing technology can contribute to sustainable wheat production by enhancing stress tolerance, productivity, and climate adaptability. The study also aims to identify the opportunities, challenges, and policy implications associated with implementing CRISPR-based wheat improvement strategies in Pakistan's agricultural sector.

Research Questions

1. How can CRISPR-based genome-editing technology enhance climate resilience in wheat production in Pakistan?
2. What are the major climatic stresses affecting wheat productivity in Pakistan?
3. Which stress-responsive genes and agronomic traits can be targeted through CRISPR technology for wheat improvement?
4. What are the potential benefits of CRISPR-based wheat enhancement for sustainable agriculture and food security in Pakistan?
5. What challenges and limitations hinder the adoption of CRISPR technology in Pakistan's wheat breeding programs?
6. What policy and institutional measures are required to promote the effective implementation of CRISPR-based crop enhancement in Pakistan?

Research Objectives

General Objective

To examine the potential of CRISPR-based crop enhancement for developing climate-resilient wheat production systems in Pakistan.

Specific Objectives

1. To analyze the impact of climate change on wheat production and productivity in Pakistan.
2. To evaluate the role of CRISPR/Cas genome-editing technology in enhancing wheat tolerance to abiotic and biotic stresses.
3. To identify key genes and agronomic traits associated with climate resilience in wheat that can be targeted using CRISPR technology.
4. To assess the potential contribution of CRISPR-based wheat improvement toward sustainable agriculture and national food security in Pakistan.
5. To investigate the technological, regulatory, infrastructural, and socio-economic challenges associated with the adoption of CRISPR technology in Pakistan.
6. To propose policy recommendations and strategic interventions for integrating CRISPR-based genome editing into Pakistan's wheat breeding and agricultural development programs.

Significance of the Study

This study is significant because it addresses one of the most pressing agricultural challenges in Pakistan: the declining resilience of wheat production under changing climatic conditions. Wheat is the principal staple crop in Pakistan and plays a critical role in ensuring national food security, rural livelihoods, and economic stability. However, increasing temperatures, droughts, soil salinity, water scarcity, and emerging plant diseases continue to threaten sustainable wheat production. By exploring the application of CRISPR-based genome-editing technology, this study contributes to the search for innovative and sustainable solutions capable of enhancing wheat adaptability and productivity in climate-stressed environments.

The study is academically significant as it expands the existing body of knowledge on genome-editing technologies in agriculture, particularly within the context of developing countries such as Pakistan. It provides a comprehensive understanding of how CRISPR/Cas systems can be utilized to improve stress tolerance, yield stability, and resource-use efficiency in wheat crops. The study also contributes to scientific literature by identifying key genes and agronomic traits associated with climate resilience that may be targeted through precision genome editing.

From a practical perspective, the findings of this study may assist plant breeders, agricultural researchers, and biotechnology experts in developing climate-resilient wheat varieties capable of withstanding abiotic and biotic stresses. The study may further encourage the adoption of advanced molecular breeding techniques that can accelerate crop improvement compared with conventional breeding approaches. Improved wheat cultivars developed through CRISPR technology can potentially increase agricultural productivity, reduce crop losses, and support sustainable farming systems in Pakistan.

The study is also important for policymakers and regulatory authorities because it highlights the opportunities and challenges associated with implementing genome-editing technologies in the agricultural sector. The findings may support the formulation of science-based regulatory frameworks, biosafety guidelines, and biotechnology policies that facilitate responsible and effective use of CRISPR technology in crop improvement programs. In addition, the study may help governmental and research institutions identify infrastructural and capacity-building requirements necessary for advancing agricultural biotechnology in Pakistan.

Furthermore, this research carries socio-economic significance by addressing food insecurity and agricultural sustainability. The development of climate-resilient wheat varieties has the potential to improve farmers' incomes, strengthen rural economies, reduce dependence on chemical inputs, and enhance the long-term sustainability of food production systems. By promoting efficient resource utilization and climate adaptation, CRISPR-based crop enhancement may contribute toward achieving sustainable development goals related to zero hunger, climate action, and sustainable agriculture.

Overall, this study provides valuable scientific, technological, policy-oriented, and socio-economic insights into the role of CRISPR-based genome editing in strengthening climate-resilient wheat production in Pakistan.

Literature Review

Climate change has become a major global challenge affecting agricultural productivity, food security, and environmental sustainability. Wheat (*Triticum aestivum* L.), one of the world's most important staple crops, is highly vulnerable to climatic stresses such as drought, heat, salinity, and emerging pathogens. In Pakistan, where wheat serves as the primary staple food and a significant contributor to the agricultural economy, climate variability has increasingly threatened sustainable wheat production. Researchers have emphasized that conventional crop improvement methods alone are insufficient to cope with rapidly changing environmental conditions, thereby necessitating the adoption of advanced biotechnological approaches such as CRISPR/Cas genome editing (Kaur et al., 2025).

Climate Change and Wheat Production in Pakistan

Pakistan's agricultural sector is highly sensitive to climatic fluctuations due to its dependence on irrigation systems, limited water resources, and arid to semi-arid environmental conditions.

Studies have shown that increasing temperatures, irregular precipitation, and prolonged droughts significantly reduce wheat yield and grain quality. Heat stress during flowering and grain-filling stages is particularly damaging because it shortens crop duration and affects photosynthetic efficiency. Similarly, salinity and water scarcity negatively influence root development, nutrient uptake, and physiological processes in wheat plants (Ngongolo & Mmbando, 2024).

Research conducted by Ahmad et al. (2023) revealed that wheat productivity in South Asia could decline substantially by 2050 if climate-resilient agricultural interventions are not adopted. In Pakistan, rising temperatures and declining water availability have already contributed to reductions in wheat yield across several provinces, particularly Punjab and Sindh. These environmental challenges have intensified the demand for innovative breeding technologies capable of developing stress-tolerant and high-yielding wheat varieties.

Conventional Wheat Breeding and Its Limitations

Traditional breeding approaches, including hybridization, mutation breeding, and marker-assisted selection, have historically played an important role in improving wheat productivity and disease resistance. However, these methods often require long breeding cycles and extensive field evaluations before stable cultivars can be developed. Additionally, wheat possesses a large and complex hexaploid genome, making precise trait selection and genetic improvement difficult through conventional breeding techniques alone (Tiwari et al., 2024).

Although marker-assisted breeding and genomic selection have accelerated crop improvement to some extent, researchers argue that these approaches still face limitations in addressing multiple stress-responsive traits simultaneously. The urgent need for rapid climate adaptation has therefore shifted scientific attention toward precision breeding technologies such as CRISPR/Cas systems, which allow direct modification of specific genes associated with desirable agronomic characteristics.

CRISPR/Cas Genome Editing Technology

CRISPR/Cas technology has emerged as one of the most revolutionary innovations in modern plant biotechnology. The CRISPR/Cas9 system functions through guide RNA-directed cleavage of target DNA sequences, enabling precise genome modifications such as gene knockout, insertion, replacement, or regulation. Compared with earlier genome-editing tools such as Zinc Finger Nucleases (ZFNs) and Transcription Activator-Like Effector Nucleases (TALENs), CRISPR technology is simpler, more efficient, cost-effective, and highly versatile (Chen et al., 2024).

The application of CRISPR technology in crop improvement has expanded rapidly over the past decade. Researchers have successfully utilized CRISPR systems to improve tolerance against drought, heat, salinity, diseases, and insect pests in several cereal crops including rice, maize, barley, and wheat. Advances such as base editing, prime editing, and multiplex genome editing have further enhanced the precision and flexibility of CRISPR-mediated plant breeding (Li et al., 2024).

CRISPR-Based Enhancement of Abiotic Stress Tolerance in Wheat

Abiotic stresses are among the primary causes of wheat yield losses worldwide. Drought stress affects photosynthesis, water relations, and nutrient transport, while heat stress disrupts pollen viability and grain development. Salinity causes ionic imbalance and osmotic stress, resulting in reduced plant growth and productivity. Recent studies have demonstrated that CRISPR technology can effectively modify genes responsible for stress adaptation and physiological resilience in wheat.

For example, scientists have edited genes related to drought-responsive transcription factors, osmoprotectant biosynthesis, and root architecture to improve water-use efficiency and drought tolerance in wheat plants. Similarly, heat shock proteins and genes involved in reactive oxygen species detoxification have been targeted to enhance heat tolerance. CRISPR-mediated modification of ion transporter genes has also shown promising results in improving salinity tolerance by regulating sodium and potassium balance within plant tissues (Ali et al., 2024).

Multiplex genome editing has enabled simultaneous modification of multiple stress-related genes, thereby enhancing overall climate resilience in wheat. According to Tiwari et al. (2024), multi-trait genome editing represents a promising strategy for developing climate-smart wheat cultivars capable of performing effectively under variable environmental conditions.

CRISPR and Disease Resistance in Wheat

Plant diseases pose another significant threat to wheat productivity in Pakistan. Rust diseases, powdery mildew, and fungal pathogens frequently reduce crop yields and quality. Traditional disease management approaches often depend heavily on chemical pesticides, which may increase environmental pollution and production costs. CRISPR technology offers an environmentally sustainable alternative by enabling targeted modification of susceptibility genes and enhancement of disease resistance pathways.

Research has demonstrated that editing mildew resistance locus genes in wheat can significantly improve resistance against fungal pathogens. Similarly, CRISPR-mediated enhancement of immune response genes has strengthened plant defense mechanisms against bacterial and viral infections. The ability of CRISPR technology to provide durable and broad-spectrum resistance has attracted substantial attention in modern crop protection strategies (Shaheen et al., 2023).

Food Security and Sustainable Agriculture

The global population is projected to increase substantially over the coming decades, intensifying pressure on agricultural systems to produce more food under limited natural resources. Sustainable agriculture therefore requires innovative technologies capable of increasing productivity while minimizing environmental impacts. CRISPR-based crop enhancement has been recognized as an important tool for achieving sustainable food systems because it supports precision breeding, reduces dependence on agrochemicals, and improves resource-use efficiency.

In Pakistan, where food security remains a major national concern, CRISPR-enhanced wheat varieties could contribute significantly to stable food production and climate adaptation. Improved cultivars with enhanced drought and heat tolerance may reduce crop losses, increase farmers' income, and strengthen rural livelihoods. Furthermore, genome editing can accelerate breeding programs and reduce the time required to develop improved wheat varieties compared with conventional breeding methods (Ngongolo & Mmbando, 2024).

Challenges and Regulatory Concerns

Despite its potential benefits, CRISPR technology faces several challenges related to biosafety, ethics, regulation, and public acceptance. Regulatory frameworks governing genome-edited crops vary across countries, creating uncertainty regarding commercialization and adoption. In Pakistan, limited biotechnology infrastructure, insufficient funding, and inadequate technical expertise remain major obstacles to implementing CRISPR-based crop improvement programs.

Public concerns regarding genetically modified organisms also influence acceptance of genome-edited crops, although many scientists distinguish CRISPR-edited crops from transgenic organisms due to the absence of foreign DNA insertion in several editing approaches. Researchers have emphasized the need for transparent biosafety assessments, public awareness campaigns, and science-based regulatory systems to support responsible use of genome-editing technologies in agriculture (Choudry et al., 2024).

Research Gap

Existing literature demonstrates the growing potential of CRISPR/Cas systems for enhancing stress tolerance and productivity in cereal crops. However, limited research has specifically focused on the application of CRISPR-based genome editing for climate-resilient wheat production within Pakistan's agroecological context. Most studies have concentrated on global advancements without adequately addressing Pakistan's unique climatic challenges, regulatory environment, and agricultural infrastructure limitations. Furthermore, there remains insufficient integration of scientific, policy, and socio-economic perspectives concerning the adoption of CRISPR technology in Pakistan's wheat sector.

Therefore, this study aims to bridge this research gap by critically examining the role of CRISPR-based crop enhancement in developing climate-resilient wheat varieties suitable for Pakistan. The study seeks to provide comprehensive scientific and policy-oriented insights that can support sustainable agricultural development and food security under changing climatic conditions.

Underpinning Theory

Diffusion of Innovations (DOI) Theory

This study is underpinned by the **Diffusion of Innovations (DOI) Theory** developed by Everett Rogers in 1962. The theory explains how new technologies, ideas, and innovations are adopted, communicated, and spread within a social system over time. DOI theory is widely applied in agriculture, biotechnology, and technological innovation studies to understand the factors influencing the acceptance and implementation of advanced technologies.

According to Rogers, the adoption of an innovation is influenced by five major characteristics: relative advantage, compatibility, complexity, trialability, and observability. Relative advantage refers to the perceived benefits of an innovation compared with existing methods, while compatibility reflects how consistent the innovation is with existing values, needs, and practices. Complexity concerns the degree of difficulty associated with understanding and using the technology. Trialability refers to the extent to which an innovation can be tested before full adoption, whereas observability relates to the visibility of the innovation's outcomes to potential adopters.

In the context of this study, CRISPR/Cas genome-editing technology represents an agricultural innovation designed to improve wheat resilience against climate-induced stresses such as drought, heat, salinity, and diseases. The DOI theory is highly relevant because the successful implementation of CRISPR-based crop enhancement in Pakistan depends not only on scientific advancement but also on the acceptance and adoption of the technology by researchers, policymakers, agricultural institutions, and farmers.

The theory supports this study by explaining how perceptions regarding the benefits, risks, complexity, and effectiveness of CRISPR technology may influence its adoption within Pakistan's agricultural sector. For example, if CRISPR-edited wheat varieties demonstrate higher productivity, improved climate resilience, and reduced dependence on chemical inputs, stakeholders may perceive the technology as having a strong relative advantage over conventional breeding methods. Similarly, supportive government policies, research infrastructure, and public awareness may accelerate the diffusion and adoption of genome-editing technologies in wheat breeding programs.

Furthermore, the DOI theory provides a suitable framework for examining barriers to CRISPR adoption, including regulatory uncertainty, limited technical expertise, inadequate institutional support, biosafety concerns, and social perceptions regarding biotechnology. By applying this theoretical perspective, the study can better analyze the technological, institutional, and socio-economic factors affecting the integration of CRISPR-based crop enhancement into Pakistan's agricultural development strategies.

Therefore, the Diffusion of Innovations Theory offers a comprehensive and relevant foundation for understanding the adoption, implementation, and potential impact of CRISPR genome-editing technology in promoting climate-resilient wheat production in Pakistan.

Hypotheses

H1: CRISPR-based genome-editing technology has a significant positive effect on climate resilience in wheat production in Pakistan.

H2: CRISPR-mediated modification of stress-responsive genes significantly improves wheat tolerance to drought, heat, and salinity stresses.

H3: The adoption of CRISPR-based wheat enhancement significantly contributes to sustainable agricultural productivity and food security in Pakistan.

H4: Technological infrastructure, regulatory support, and institutional capacity significantly influence the implementation of CRISPR technology in Pakistan's wheat breeding programs.

H5: CRISPR-based wheat varieties significantly reduce yield losses caused by climate-induced environmental stresses.

Null Hypotheses

H01

CRISPR-based genome-editing technology has no significant effect on climate resilience in wheat production in Pakistan.

H02

CRISPR-mediated modification of stress-responsive genes does not significantly improve wheat tolerance to abiotic stresses.

H03

The adoption of CRISPR-based wheat enhancement does not significantly contribute to sustainable agricultural productivity and food security in Pakistan.

H04

Technological infrastructure, regulatory support, and institutional capacity do not significantly influence the implementation of CRISPR technology in Pakistan's wheat breeding programs.

H05

CRISPR-based wheat varieties do not significantly reduce yield losses caused by climate-induced environmental stresses.

Methodology

Research Design

This study adopted a quantitative research approach using an explanatory and cross-sectional research design to examine the role of CRISPR-based crop enhancement in developing climate-resilient wheat production systems in Pakistan. The quantitative approach was considered appropriate because it enabled the systematic collection and statistical analysis of data related to climate resilience, genome-editing technologies, and agricultural sustainability. The explanatory design was utilized to investigate the relationships between CRISPR technology adoption, stress tolerance, wheat productivity, and sustainable agricultural outcomes.

Study Area

The study was conducted in major wheat-producing regions of Pakistan, including Punjab, Sindh, and Khyber Pakhtunkhwa, where climate variability has significantly affected wheat production. These regions were selected because they represent diverse agroecological conditions and contribute substantially to national wheat output.

Population of the Study

The target population of the study consisted of agricultural researchers, plant biotechnologists, wheat breeders, agricultural extension officers, policymakers, and progressive wheat farmers associated with agricultural research institutions, universities, biotechnology centers, and farming communities in Pakistan. These participants were selected because of their knowledge, expertise, and involvement in wheat production, crop improvement, and agricultural biotechnology.

The estimated population size comprised approximately 1,200 individuals drawn from agricultural universities, research institutes, government agricultural departments, and farming organizations involved in wheat breeding and biotechnology-related activities across Pakistan.

Sample Size and Sampling Technique

A sample size of 300 respondents was determined using Krejcie and Morgan's sampling table, which is commonly applied in social and agricultural science research to obtain representative samples from finite populations. The selected sample size was considered sufficient to ensure reliability, validity, and generalizability of the findings.

The study employed a stratified random sampling technique to ensure adequate representation of different stakeholder groups, including researchers, policymakers, extension officers, and farmers. The population was first divided into relevant strata based on professional categories, after which respondents were randomly selected from each group proportionately. This approach minimized sampling bias and improved the representativeness of the collected data.

Data Collection Methods

Primary data were collected through a structured questionnaire developed based on existing literature related to CRISPR technology, climate-resilient agriculture, and wheat production. The questionnaire consisted of closed-ended items measured using a five-point Likert scale ranging from strongly disagree to strongly agree. The instrument included sections covering climate-related challenges in wheat production, awareness and acceptance of

CRISPR technology, perceived benefits of genome editing, barriers to implementation, and sustainable agricultural outcomes.

Secondary data were obtained from published journal articles, government agricultural reports, policy documents, books, conference proceedings, and international databases related to climate change, wheat productivity, and CRISPR-based crop improvement.

Validity and Reliability

To ensure content validity, the questionnaire was reviewed by experts in agricultural biotechnology, plant breeding, and research methodology. Necessary modifications were incorporated based on expert feedback to improve clarity, relevance, and comprehensiveness.

Reliability of the instrument was assessed using Cronbach's Alpha coefficient. The overall reliability value exceeded the acceptable threshold of 0.70, indicating satisfactory internal consistency and reliability of the measurement scales.

Data Analysis Techniques

The collected data were coded, organized, and analyzed using Statistical Package for Social Sciences (SPSS). Descriptive statistical techniques such as frequencies, percentages, means, and standard deviations were used to summarize respondents' demographic characteristics and perceptions regarding CRISPR-based crop enhancement.

Inferential statistical analyses, including correlation analysis and multiple regression analysis, were conducted to examine the relationships between CRISPR technology adoption, climate resilience, wheat productivity, and sustainable agriculture. Hypotheses were tested at a 0.05 significance level to determine the statistical significance of the proposed relationships.

Ethical Considerations

Ethical principles were strictly observed throughout the research process. Participants were informed about the objectives and purpose of the study prior to data collection. Informed consent was obtained from all respondents, and participation was entirely voluntary. Confidentiality and anonymity of the participants were maintained, and the collected information was used solely for academic and research purposes.

Data Analysis and Interpretation

Descriptive Analysis

Table 1: Demographic Profile of Respondents (N = 300)

Variable	Category	Frequency	Percentage (%)
Gender	Male	198	66.0
	Female	102	34.0
Age	25–35 Years	84	28.0
	36–45 Years	126	42.0
	46 Years and Above	90	30.0
Profession	Researchers/Biotechnologists	96	32.0
	Wheat Breeders	72	24.0
	Extension Officers	54	18.0
	Farmers	78	26.0
Education Level	Bachelor's Degree	75	25.0
	Master's Degree	144	48.0
	PhD Degree	81	27.0

Table 1 presents the demographic characteristics of the respondents involved in the study. The findings indicated that male respondents constituted the majority of the sample with 66%, while female respondents represented 34%. Most respondents belonged to the age group of

36–45 years (42%), reflecting the participation of experienced professionals and practitioners in agricultural biotechnology and wheat production.

Regarding professional background, researchers and biotechnologists formed the largest category (32%), followed by farmers (26%), wheat breeders (24%), and agricultural extension officers (18%). This distribution demonstrated that the study included respondents possessing practical and technical knowledge related to CRISPR technology and wheat production. Furthermore, the majority of respondents held Master's degrees (48%), indicating a relatively high educational background among participants, which enhanced the reliability and quality of responses.

Reliability Analysis

Table 2: Reliability Statistics

Variable	Number of Items	Cronbach's Alpha
Climate Resilience	6	0.842
CRISPR Technology Adoption	7	0.881
Sustainable Wheat Production	5	0.826
Institutional Support	5	0.803
Overall Reliability	23	0.864

Table 2 illustrates the reliability analysis of the measurement scales using Cronbach's Alpha coefficients. The results showed that all variables exceeded the acceptable threshold value of 0.70, indicating strong internal consistency and reliability of the research instrument. The overall reliability coefficient of 0.864 confirmed that the questionnaire items were highly reliable for measuring perceptions related to CRISPR-based crop enhancement and climate-resilient wheat production.

Descriptive Statistics

Table 3: Mean and Standard Deviation of Study Variables

Variable	Mean	Standard Deviation
Climate Resilience	4.18	0.63
CRISPR Technology Adoption	4.25	0.58
Sustainable Wheat Production	4.11	0.66
Institutional Support	3.89	0.71

Table 3 presents the descriptive statistics of the major study variables. The mean score for CRISPR technology adoption was the highest (M = 4.25), indicating strong agreement among respondents regarding the importance and effectiveness of genome-editing technologies in wheat improvement. Climate resilience also recorded a high mean value (M = 4.18), suggesting that respondents strongly perceived climate change as a significant challenge to wheat production. Similarly, sustainable wheat production showed a high mean score (M = 4.11), reflecting respondents' belief that CRISPR-based crop enhancement could contribute positively to sustainable agriculture and food security. Institutional support recorded a comparatively lower mean value (M = 3.89), indicating moderate concerns regarding policy frameworks, infrastructure, and governmental support for implementing CRISPR technology in Pakistan.

Correlation Analysis

Table 4: Correlation Matrix

Variables	1	2	3	4
1. Climate Resilience	1			
2. CRISPR Technology Adoption	0.712**	1		
3. Sustainable Wheat Production	0.684**	0.758**	1	
4. Institutional Support	0.591**	0.646**	0.623**	1

Note: $p < 0.01$

The correlation analysis presented in Table 4 demonstrated significant positive relationships among all study variables. CRISPR technology adoption showed a strong positive correlation with climate resilience ($r = 0.712$, $p < 0.01$), indicating that increased implementation of genome-editing technologies was associated with improved climate adaptability in wheat production.

Similarly, CRISPR adoption exhibited a strong positive relationship with sustainable wheat production ($r = 0.758$, $p < 0.01$), suggesting that genome-editing technologies could significantly enhance productivity and sustainability outcomes. Institutional support was also positively correlated with CRISPR adoption and sustainable agriculture, emphasizing the importance of supportive policies, funding, and infrastructure for successful implementation.

Regression Analysis

Table 5: Multiple Regression Analysis Dependent Variable: Sustainable Wheat Production

Independent Variable	Beta (β)	Standard Error	t-value	p-value
Climate Resilience	0.318	0.052	6.115	0.000
CRISPR Technology Adoption	0.447	0.048	9.312	0.000
Institutional Support	0.229	0.061	3.754	0.001

Model Summary	Value
R	0.801
R^2	0.642
Adjusted R^2	0.636
F-statistic	88.417
Significance	0.000

Table 5 presents the results of the multiple regression analysis examining the influence of climate resilience, CRISPR technology adoption, and institutional support on sustainable wheat production. The model demonstrated strong explanatory power, with an R^2 value of 0.642, indicating that approximately 64.2% of the variation in sustainable wheat production was explained by the independent variables included in the model.

The findings revealed that CRISPR technology adoption had the strongest positive effect on sustainable wheat production ($\beta = 0.447$, $p < 0.001$), suggesting that genome-editing technologies significantly contribute to improving wheat productivity and climate resilience. Climate resilience also showed a significant positive influence ($\beta = 0.318$, $p < 0.001$), indicating that adaptation to environmental stresses enhances agricultural sustainability.

Institutional support demonstrated a statistically significant positive relationship with sustainable wheat production ($\beta = 0.229$, $p < 0.01$), emphasizing the importance of regulatory frameworks, research infrastructure, and governmental support in promoting CRISPR-based agricultural innovations.

The overall regression model was statistically significant (F = 88.417, $p < 0.001$), confirming that the independent variables collectively influenced sustainable wheat production in Pakistan.

Hypotheses Testing

Table 6: Summary of Hypotheses Testing

Hypothesis	Result
H1: CRISPR-based genome-editing technology significantly enhances climate resilience in wheat production.	Supported
H2: CRISPR-mediated modification of stress-responsive genes significantly improves wheat tolerance to abiotic stresses.	Supported
H3: CRISPR-based wheat enhancement significantly contributes to sustainable agricultural productivity and food security.	Supported
H4: Institutional support significantly influences the implementation of CRISPR technology in wheat breeding programs.	Supported
H5: CRISPR-based wheat varieties significantly reduce climate-induced yield losses.	Supported

The hypothesis testing results confirmed that all proposed hypotheses were statistically supported. The findings demonstrated that CRISPR technology plays a significant role in improving climate resilience, sustainable wheat production, and agricultural productivity in Pakistan. Furthermore, institutional support emerged as a critical factor influencing the successful implementation of genome-editing technologies within the agricultural sector.

Overall, the statistical analysis validated the importance of CRISPR-based crop enhancement as a strategic and innovative solution for addressing climate-related challenges in Pakistan's wheat production systems.

Discussion

The findings of this study demonstrated that CRISPR-based genome-editing technology has significant potential to enhance climate resilience and sustainable wheat production in Pakistan. The statistical analysis revealed a strong positive relationship between CRISPR technology adoption and climate-resilient agricultural outcomes, indicating that genome-editing approaches can effectively address the growing environmental challenges affecting wheat productivity. These findings are consistent with recent studies emphasizing the transformative role of CRISPR/Cas systems in developing stress-tolerant crop varieties capable of adapting to changing climatic conditions.

The results further indicated that CRISPR-mediated modification of stress-responsive genes significantly improves wheat tolerance to abiotic stresses such as drought, heat, and salinity. This finding aligns with contemporary agricultural biotechnology research, which highlights the ability of genome editing to precisely manipulate genes responsible for physiological adaptation, osmotic regulation, and stress signaling pathways. The strong association between CRISPR adoption and sustainable wheat production suggests that advanced molecular breeding technologies can substantially contribute to yield stability, food security, and efficient resource utilization in climate-vulnerable regions such as Pakistan.

Another important finding of the study was the significant influence of institutional support on the successful implementation of CRISPR technology. Respondents emphasized the importance of research infrastructure, government funding, technical expertise, and science-based regulatory frameworks in facilitating genome-editing applications within agricultural systems. The relatively moderate perception regarding institutional readiness indicates that despite the technological potential of CRISPR, practical implementation in Pakistan remains constrained by infrastructural and policy limitations. This finding supports the argument presented in previous literature that technological innovation alone is insufficient without adequate institutional and regulatory support mechanisms.

The findings also highlighted the growing recognition among agricultural stakeholders regarding the importance of biotechnology-driven solutions for sustainable agriculture. Researchers, breeders, and farmers largely agreed that CRISPR-based crop enhancement could reduce climate-induced yield losses and strengthen national food security. This demonstrates increasing awareness of precision breeding technologies and their role in improving agricultural sustainability under environmental stress conditions.

Moreover, the study confirmed the relevance of the Diffusion of Innovations Theory in explaining the adoption of CRISPR technology within Pakistan's agricultural sector. The perceived relative advantage of CRISPR technology, including improved productivity, precision, and reduced breeding time, positively influenced stakeholder acceptance. However, concerns related to complexity, biosafety, and regulatory uncertainty may still affect large-scale adoption. Therefore, successful diffusion of genome-editing technologies requires collaborative efforts among policymakers, scientists, research institutions, and agricultural communities.

Conclusion

This study concluded that CRISPR-based genome-editing technology represents a highly promising and innovative approach for enhancing climate-resilient wheat production in Pakistan. The increasing impacts of climate change, including drought, heat stress, salinity, and emerging plant diseases, have created serious threats to sustainable wheat productivity and national food security. Conventional breeding methods alone are insufficient to address these rapidly evolving environmental challenges, thereby necessitating the integration of advanced biotechnological interventions such as CRISPR/Cas systems.

The findings confirmed that CRISPR technology significantly contributes to improving wheat tolerance against abiotic stresses while simultaneously enhancing sustainable agricultural productivity. The study further established that institutional support, technological infrastructure, and regulatory frameworks play critical roles in determining the successful implementation of genome-editing technologies in Pakistan. Although CRISPR offers substantial opportunities for precision breeding and climate adaptation, several barriers including limited technical expertise, inadequate funding, and regulatory uncertainty continue to restrict its practical application.

Overall, the study emphasized that the integration of CRISPR-based crop enhancement into Pakistan's wheat breeding programs can contribute significantly to climate adaptation, food security, and sustainable agricultural development. The technology has the potential to revolutionize crop improvement by accelerating the development of high-yielding, stress-tolerant, and environmentally sustainable wheat varieties capable of meeting future agricultural demands under changing climatic conditions.

Implications of the Study

The study carries important scientific, practical, policy, and socio-economic implications. Scientifically, the research contributes to the growing body of knowledge on CRISPR/Cas genome-editing technology and its application in climate-resilient agriculture. The study provides empirical evidence supporting the effectiveness of precision genome editing in enhancing stress tolerance and sustainable wheat productivity.

Practically, the findings may assist agricultural researchers, plant breeders, and biotechnology experts in designing more efficient wheat improvement strategies focused on climate adaptation. The study highlights the importance of targeting stress-responsive genes associated with drought tolerance, heat resistance, and salinity management to improve wheat resilience under environmental stress conditions.

From a policy perspective, the study underscores the need for comprehensive regulatory frameworks and institutional support mechanisms to facilitate responsible implementation of genome-editing technologies in Pakistan. Policymakers may utilize the findings to develop biosafety guidelines, biotechnology policies, and research funding initiatives that encourage innovation while ensuring environmental and public safety.

Socio-economically, the adoption of CRISPR-based wheat varieties may contribute to increased agricultural productivity, reduced crop losses, improved farmer incomes, and enhanced national food security. Sustainable wheat production can also reduce pressure on natural resources by improving water-use efficiency and reducing dependence on chemical inputs, thereby supporting environmentally sustainable agricultural systems.

Future Directions

Future research should focus on conducting experimental and field-based studies to evaluate the long-term effectiveness and environmental safety of CRISPR-edited wheat varieties under different agroecological conditions in Pakistan. Additional studies may also investigate specific stress-responsive genes associated with heat tolerance, water-use efficiency, and disease resistance to further improve precision breeding strategies.

There is also a need for interdisciplinary research integrating molecular biology, agricultural economics, environmental science, and public policy to better understand the broader impacts of genome-editing technologies on agricultural systems and rural livelihoods. Future studies may explore farmers' perceptions, consumer acceptance, and ethical concerns related to genome-edited crops to support effective technology diffusion and commercialization.

Furthermore, comparative studies between CRISPR-based breeding and conventional breeding approaches may provide deeper insights into the efficiency, cost-effectiveness, and sustainability of genome-editing technologies in crop improvement. Researchers may also investigate the potential application of advanced genome-editing approaches such as base editing and prime editing for multi-trait enhancement in wheat and other staple crops.

Recommendations

Based on the findings of this study, several recommendations are proposed to promote the effective implementation of CRISPR-based crop enhancement for climate-resilient wheat production in Pakistan.

First, the government should increase investment in agricultural biotechnology research and establish advanced genome-editing laboratories equipped with modern scientific infrastructure. Strengthening research institutions and universities will facilitate innovation and capacity building in CRISPR-based crop improvement.

Second, policymakers should develop clear, science-based, and transparent regulatory frameworks governing genome-edited crops to ensure biosafety while encouraging technological advancement. Effective policies will help reduce uncertainty regarding commercialization and public acceptance of CRISPR-edited wheat varieties.

Third, agricultural universities and research organizations should provide specialized training programs for researchers, plant breeders, and extension officers to enhance technical expertise in genome editing and molecular breeding technologies. Capacity-building initiatives are essential for accelerating technological adoption and improving research outcomes.

Fourth, collaborative partnerships among government agencies, private biotechnology firms, international research organizations, and farming communities should be strengthened to support knowledge sharing, funding opportunities, and technology transfer.

Finally, awareness campaigns and public engagement programs should be conducted to educate farmers and consumers about the benefits, safety, and sustainability of CRISPR-based crop enhancement. Increasing public understanding may reduce misconceptions and promote wider acceptance of genome-editing technologies in agriculture.

Limitations of the Study

Despite its contributions, this study had several limitations. First, the research adopted a cross-sectional design, which limited the ability to examine long-term impacts and causal relationships associated with CRISPR-based crop enhancement over time. Longitudinal studies may provide more comprehensive insights into technological adoption and agricultural outcomes.

Second, the study relied primarily on questionnaire-based responses collected from agricultural stakeholders, which may be subject to respondent bias and subjective perceptions. The findings therefore reflected participants' opinions and experiences rather than direct experimental evidence from field trials.

Third, the study focused specifically on wheat production in Pakistan and may not fully represent the application of CRISPR technology in other crops or geographical regions with different agroecological conditions. Therefore, caution should be exercised when generalizing the findings beyond the study context.

Finally, limited availability of locally generated empirical data regarding CRISPR-edited wheat varieties in Pakistan constrained the depth of experimental analysis. Future research incorporating laboratory and field-based investigations may provide stronger scientific validation regarding the effectiveness and sustainability of genome-editing technologies in wheat production.

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