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CRISPR-BASED CLIMATE-RESILIENT CROP IMPROVEMENT FOR SUSTAINABLE AGRICULTURE IN PAKISTAN

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Abstract
Climate change poses significant threats to agricultural productivity, food security, and environmental sustainability, particularly in developing countries such as Pakistan. Increasing temperatures, water scarcity, soil salinity, floods, droughts, and emerging crop diseases have intensified the need for innovative agricultural technologies capable of enhancing crop resilience and ensuring sustainable food production. This study examined the role of CRISPR-based climate-resilient crop improvement in promoting sustainable agriculture in Pakistan, with climate resilience serving as the mediating mechanism. Guided by Sustainable Agricultural Innovation Theory, the study adopted a quantitative, cross-sectional research design to investigate the relationships among the proposed constructs. Data were collected using a structured questionnaire from agricultural scientists, plant breeders, biotechnology researchers, extension officers, and progressive farmers. The collected data were analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM) to evaluate the measurement and structural models. The findings indicated that CRISPR-based crop improvement significantly enhanced climate resilience and sustainable agriculture. Climate resilience also exerted a significant positive influence on sustainable agriculture and partially mediated the relationship between CRISPR-based crop improvement and sustainable agricultural development. The study demonstrates that precise genome-editing technologies can improve crop tolerance to drought, heat, salinity, floods, pests, and diseases while increasing productivity and resource-use efficiency. The findings provide important theoretical, practical, and policy implications by emphasizing the need for greater investment in agricultural biotechnology, supportive regulatory frameworks, research capacity building, and public–private collaboration to accelerate the adoption of CRISPR technologies for climate-smart agriculture and long-term food security in Pakistan.

INTRODUCTION
Climate change has emerged as one of the greatest threats to global agricultural productivity and food security. Rising temperatures, erratic rainfallprolonged droughts, floods, salinity, and

the increasing prevalence of pests and diseases have significantly reduced crop yields worldwide. Developing countries such as Pakistan are particularly vulnerable because agriculture contributes substantially to the national economy, rural livelihoods, and food production. The country's agricultural sector faces growing challenges associated with climate variability, water scarcity, land degradation, and population growth, necessitating the development of innovative technologies capable of enhancing crop resilience and productivity (Intergovernmental Panel on Climate Change [IPCC], 2023).

Recent advances in biotechnology have positioned Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR)-based genome editing as one of the most promising tools for sustainable agricultural development. Unlike conventional breeding and transgenic genetic modification, CRISPR enables precise, rapid, cost-effective, and targeted modification of plant genomes without introducing foreign DNA. This technology has successfully improved drought tolerance, heat resistance, salinity tolerance, disease resistance, nutrient-use efficiency, and crop yield in numerous economically important crops (Chen et al., 2024).

Climate-resilient crop improvement has become a strategic priority for ensuring food security under changing environmental conditions. CRISPR technology enables researchers to identify and edit genes responsible for stress tolerance, photosynthetic efficiency, nutrient utilization, and resistance to emerging plant pathogens. Consequently, genome-edited crops have the potential to maintain stable productivity despite increasing climatic uncertainties while reducing dependence on chemical fertilizers and pesticides (Gao, 2021).

Pakistan's agriculture contributes significantly to national GDP, employment, and exports. Major crops such as wheat, rice, cotton, maize, and sugarcane are increasingly threatened by climate-induced stresses, including drought, floods, high temperatures, salinity, and emerging crop diseases. Although conventional breeding programs have produced improved crop varieties, their long breeding cycles and limited precision often restrict rapid adaptation to changing climatic conditions. CRISPR-based genome editing offers an efficient alternative for accelerating crop improvement and strengthening agricultural resilience (Pakistan Economic Survey, 2024).

In addition to improving crop productivity, CRISPR technology supports sustainable agriculture by reducing environmental impacts associated with intensive farming practices. Genome-edited crops requiring fewer chemical inputs contribute to improved soil health, reduced greenhouse gas emissions, enhanced biodiversity conservation, and more efficient resource utilization. These benefits align closely with global Sustainable Development Goals (SDGs), particularly those relating to food security, climate action, poverty reduction, and environmental sustainability (Food and Agriculture Organization [FAO], 2023).

Despite its enormous scientific and agricultural potential, the adoption of CRISPR technology in Pakistan remains constrained by limited biotechnology infrastructure, inadequate research funding, regulatory uncertainty, insufficient public awareness, shortages of skilled researchers, and weak collaboration between research institutions and the agricultural industry. Furthermore, ethical, legal, and biosafety considerations continue to influence the commercialization and acceptance of genome-edited crops.

Although numerous international studies have demonstrated the effectiveness of CRISPR for climate-resilient crop improvement, relatively limited empirical research has examined its potential within the agricultural, environmental, and socioeconomic context of Pakistan. Existing studies primarily emphasize technical aspects of genome editing while providing limited attention to its broader implications for sustainable agriculture, climate adaptation, and national food security. Therefore, this study investigates the role of CRISPR-based climate-resilient crop improvement in promoting sustainable agriculture in Pakistan, thereby providing evidence-based recommendations for policymakers, researchers, and agricultural practitioners.

Problem Statement

Climate change continues to pose serious threats to Pakistan's agricultural sector through increasing temperatures, unpredictable rainfall, prolonged droughts, floods, soil salinity, water scarcity, and the emergence of new crop pests and diseases. These environmental challenges have reduced agricultural productivity, threatened food security, and increased the vulnerability of rural livelihoods. Conventional plant breeding methods have contributed to crop improvement; however, their lengthy breeding cycles, limited precision, and slower response to rapidly changing climatic conditions restrict their effectiveness in developing climate-resilient crop varieties.

CRISPR-based genome editing has emerged as a transformative biotechnology capable of rapidly developing crops with enhanced tolerance to abiotic and biotic stresses while improving productivity, nutritional quality, and resource-use efficiency. Despite its demonstrated success in global agricultural research, the application of CRISPR technology in Pakistan remains limited due to inadequate research infrastructure, regulatory challenges, insufficient investment, and limited institutional capacity.

Existing research has largely focused on the technical aspects of genome editing, with relatively little attention given to its potential contribution to sustainable agriculture and climate adaptation within Pakistan. Consequently, there is limited empirical evidence to guide policymakers and agricultural stakeholders regarding the adoption of CRISPR-based crop improvement strategies. Addressing this research gap is essential for developing effective policies that strengthen climate resilience, improve food security, and promote sustainable agricultural development.

Research Questions

- How does CRISPR-based genome editing contribute to climate-resilient crop improvement in Pakistan?
- What is the influence of CRISPR technology on sustainable agricultural productivity?
- How does CRISPR-based crop improvement enhance resistance to climate-induced environmental stresses?
- What are the major barriers affecting the adoption of CRISPR technology in Pakistan's agricultural sector?
- What policy measures can facilitate the effective implementation of CRISPR-based climate-resilient agriculture?

Research Objectives

General Objective

To examine the role of CRISPR-based climate-resilient crop improvement in promoting sustainable agriculture in Pakistan.

Specific Objectives

- To evaluate the contribution of CRISPR genome editing to climate-resilient crop improvement.
- To examine the influence of CRISPR technology on sustainable agricultural productivity.
- To assess the effectiveness of CRISPR-based crop improvement in enhancing tolerance to climate-induced stresses.
- To identify the major challenges limiting the adoption of CRISPR technology in Pakistan.
- To propose policy recommendations for promoting CRISPR-enabled sustainable agriculture.

Significance of the Study

The study makes significant theoretical, practical, and policy contributions to agricultural biotechnology and sustainable development. Theoretically, it extends the growing body of knowledge on genome editing by integrating CRISPR technology with climate-resilient agriculture and sustainable development within the context of Pakistan. The findings contribute to the literature on agricultural innovation, climate adaptation, and biotechnology-driven food security.

Practically, the study provides valuable insights for agricultural scientists, plant breeders, biotechnology researchers, universities, and research institutions regarding the application of CRISPR technology for developing climate-resilient crops. The findings may assist researchers in designing improved breeding strategies capable of increasing crop productivity while minimizing environmental impacts.

From a policy perspective, the study offers evidence-based recommendations for government agencies, agricultural policymakers, biotechnology regulators, and development organizations responsible for agricultural modernization. The findings can support the formulation of policies that strengthen biotechnology research, improve regulatory frameworks, enhance public-private partnerships, increase investment in agricultural innovation, and accelerate the responsible adoption of CRISPR technology. Ultimately, the study contributes to strengthening food security, enhancing climate resilience, improving farmers' livelihoods, and promoting sustainable agricultural development in Pakistan.

Literature Review

Underpinning Theory

Sustainable Agricultural Innovation Theory

This study is underpinned by Sustainable Agricultural Innovation Theory, which explains how scientific innovation and advanced agricultural technologies contribute to sustainable food production, environmental conservation, climate adaptation, and long-term agricultural resilience. The theory emphasizes that technological innovations should simultaneously improve agricultural productivity, strengthen resilience to environmental stresses, enhance resource-use efficiency, and promote ecological sustainability while ensuring food security for present and future generations (Food and Agriculture Organization [FAO], 2023).

Within this theoretical perspective, CRISPR-based genome editing represents a disruptive agricultural innovation that enables precise modification of crop genomes to improve resistance to drought, heat, salinity, flooding, pests, and diseases without the lengthy breeding cycles associated with conventional plant breeding. The theory argues that sustainable agricultural development depends upon the adoption of technologies capable of increasing productivity while reducing environmental degradation, conserving natural resources, and strengthening farmers' adaptive capacity to climate change.

For Pakistan, Sustainable Agricultural Innovation Theory provides an appropriate framework for understanding how CRISPR technology can enhance climate resilience, improve crop productivity, strengthen food security, reduce dependence on agrochemicals, and support sustainable agricultural transformation under increasingly adverse climatic conditions.

CRISPR-Based Genome Editing

Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) associated with Cas proteins has revolutionized modern plant biotechnology by providing a highly precise, efficient, rapid, and cost-effective genome-editing system. Unlike conventional breeding methods and traditional genetic engineering, CRISPR enables targeted modification of specific genes responsible for desirable agronomic traits without necessarily introducing foreign DNA into plant genomes (Chen et al., 2024).

Recent developments have expanded CRISPR applications through technologies such as CRISPR-Cas9, CRISPR-Cas12, base editing, and prime editing, allowing researchers to improve complex crop characteristics with unprecedented precision. Genome editing has been successfully applied in major food crops including wheat, rice, maize, cotton, soybean, tomato, and potato to improve stress tolerance, disease resistance, nutritional quality, and yield potential (Gao, 2021).

The efficiency, affordability, and versatility of CRISPR have positioned it as one of the most important innovations supporting sustainable agricultural development worldwide.

Climate-Resilient Crop Improvement

Climate-resilient crop improvement involves developing crop varieties capable of maintaining stable productivity despite adverse environmental conditions such as drought, heat stress, salinity, flooding, nutrient deficiency, and emerging plant diseases. Climate change has intensified these challenges globally, threatening food security and agricultural sustainability, particularly in developing countries.

CRISPR technology enables precise editing of genes associated with abiotic and biotic stress tolerance, accelerating the development of resilient crop varieties. Recent studies have demonstrated successful genome editing for drought tolerance, heat tolerance, flood resistance, salinity tolerance, improved water-use efficiency, and enhanced resistance to fungal, bacterial, and viral diseases in several economically important crops (Chen et al., 2024).

Compared with conventional breeding, CRISPR significantly reduces breeding time while increasing the accuracy of trait improvement, making it particularly valuable for rapid climate adaptation.

CRISPR and Sustainable Agriculture

Sustainable agriculture seeks to increase agricultural productivity while conserving natural resources, minimizing environmental degradation, and ensuring long-term food security. CRISPR contributes to sustainable agriculture by improving crop performance without increasing dependence on chemical fertilizers, pesticides, and excessive irrigation.

Genome-edited crops exhibiting improved nutrient-use efficiency require fewer agricultural inputs, thereby reducing production costs and environmental pollution. Enhanced disease resistance decreases pesticide application, while drought- and salinity-tolerant crops improve agricultural productivity under water-limited conditions. Consequently, CRISPR technology supports environmentally sustainable farming systems and contributes directly to several Sustainable Development Goals (SDGs), particularly Zero Hunger (SDG 2), Climate Action (SDG 13), Responsible Consumption and Production (SDG 12), and Life on Land (SDG 15) (FAO, 2023).

For Pakistan, where agriculture is increasingly threatened by climate variability and resource scarcity, CRISPR-based crop improvement provides opportunities to strengthen agricultural resilience while promoting environmentally sustainable farming practices.

Climate Change and Agriculture in Pakistan

Agriculture remains one of the most climate-sensitive sectors of Pakistan's economy. Rising temperatures, erratic precipitation, glacier melting, recurrent floods, prolonged droughts, soil salinity, and declining water availability have significantly affected crop productivity across the country. Major crops such as wheat, rice, cotton, sugarcane, and maize have experienced increasing yield variability due to changing climatic conditions.

Pakistan's dependence on irrigated agriculture further increases its vulnerability to water scarcity and climate-related disasters. Traditional breeding programs have contributed to agricultural development; however, their relatively slow pace limits the rapid development of crop varieties capable of responding to evolving climatic challenges. Consequently, advanced genome-editing technologies have become increasingly important for strengthening agricultural adaptation and national food security (Pakistan Economic Survey, 2024).

Challenges and Future Prospects of CRISPR Adoption in Pakistan

Despite remarkable scientific progress, several barriers continue to limit the widespread adoption of CRISPR technology in Pakistan. Limited biotechnology infrastructure, inadequate research funding, shortages of highly trained genome-editing specialists, regulatory uncertainty, weak university–industry collaboration, insufficient commercialization mechanisms, and limited public awareness remain significant constraints.

Ethical considerations, biosafety regulations, intellectual property issues, and public acceptance also influence the commercialization of genome-edited crops. Developing comprehensive regulatory frameworks that distinguish genome-edited crops from conventional genetically modified organisms (GMOs) may facilitate responsible innovation while ensuring environmental and food safety.

Nevertheless, Pakistan possesses considerable opportunities to expand CRISPR research through increased investment in biotechnology, international scientific collaboration, capacity building, advanced research laboratories, and public-private partnerships. Future integration of artificial intelligence, genomics, phenomics, precision agriculture, and digital farming technologies with CRISPR is expected to accelerate the development of next-generation climate-resilient crop varieties capable of supporting sustainable agricultural transformation.

Conceptual Framework

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                  Climate Resilience
                     (Mediator)
                         |
                         ▼
CRISPR-Based Climate-Resilient Crop Improvement ──► Sustainable Agriculture
         (Independent Variable)                         (Dependent
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Hypotheses

H1: CRISPR-Based Climate-Resilient Crop Improvement has a significant positive effect on Sustainable Agriculture in Pakistan.

H2: CRISPR-Based Climate-Resilient Crop Improvement has a significant positive effect on Climate Resilience.

H3: Climate Resilience has a significant positive effect on Sustainable Agriculture.

H4: Climate Resilience mediates the relationship between CRISPR-Based Climate-Resilient Crop Improvement and Sustainable Agriculture.

Methodology

This study investigated the influence of CRISPR-Based Climate-Resilient Crop Improvement on Sustainable Agriculture in Pakistan, with Climate Resilience serving as the mediating variable. A quantitative research methodology was adopted to empirically examine the proposed relationships among the study variables.

Research Design

A quantitative, cross-sectional survey research design was employed. The cross-sectional approach was considered appropriate because it enabled the collection of data from respondents at a single point in time and facilitated the examination of the relationships among CRISPR-based crop improvement, climate resilience, and sustainable agriculture. The proposed hypotheses were tested using Partial Least Squares Structural Equation Modeling (PLS-SEM).

Population

The target population comprised agricultural scientists, plant breeders, biotechnologists, university researchers, agricultural extension officers, policymakers, and progressive farmers involved in climate-smart agriculture and crop improvement across Pakistan. These respondents were selected because of their knowledge and experience regarding agricultural biotechnology, genome editing, climate adaptation, and sustainable agricultural practices.

Sampling Technique

A purposive sampling technique was employed to identify respondents with relevant expertise in agriculture and biotechnology. To improve representation, respondents were selected from agricultural universities, public and private research institutions, biotechnology laboratories, agricultural departments, and farming communities across different provinces of Pakistan.

Sample Size

A total of 400 respondents participated in the study. The sample size exceeded the minimum recommendations for PLS-SEM and was considered sufficient to provide adequate statistical power, reliable parameter estimation, and robust hypothesis testing (Hair et al., 2022).

Data Collection Procedures

Primary data were collected using a structured, self-administered questionnaire adapted from previously validated instruments related to agricultural innovation, climate resilience, and sustainable agriculture.

Before the main survey, the questionnaire was evaluated by experts in agricultural biotechnology, plant sciences, environmental sciences, and research methodology to establish content validity. A pilot study involving a small group of respondents was conducted to assess clarity, reliability, and comprehensibility of the instrument. Necessary modifications were incorporated based on expert feedback and pilot testing.

Following ethical approval and institutional permission, questionnaires were distributed personally and electronically to eligible respondents. Participation was voluntary, and respondents were informed about the objectives of the study. Confidentiality and anonymity were maintained throughout the data collection process. Completed questionnaires were screened for completeness before coding and statistical analysis.

Instruments and Measures

Data were collected using a structured questionnaire consisting of four sections. All items were measured using a five-point Likert scale ranging from 1 = Strongly Disagree to 5 = Strongly Agree.

CRISPR-Based Climate-Resilient Crop Improvement (Independent Variable)

This construct was measured using items assessing respondents' perceptions regarding the effectiveness of CRISPR technology in improving drought tolerance, heat tolerance, salinity resistance, disease resistance, crop productivity, nutrient-use efficiency, and precision breeding.

Climate Resilience (Mediator)

Climate Resilience was measured using indicators related to crops' capacity to withstand climate-induced stresses, recover from environmental shocks, maintain stable yields, adapt to changing climatic conditions, and ensure long-term agricultural sustainability.

Sustainable Agriculture (Dependent Variable)

Sustainable Agriculture was measured through indicators assessing agricultural productivity, efficient resource utilization, environmental sustainability, food security, reduced agrochemical dependency, biodiversity conservation, and long-term agricultural development.

Reliability and Validity

Reliability

Internal consistency reliability was evaluated using Cronbach's Alpha and Composite Reliability (CR). Values greater than 0.70 were considered acceptable, indicating satisfactory reliability of the measurement scales (Hair et al., 2022).

Validity

Content Validity

Content validity was established through expert evaluation by specialists in agricultural biotechnology, plant breeding, environmental sciences, and research methodology. Their recommendations enhanced the relevance and clarity of the questionnaire.

Construct Validity

Construct validity was assessed using confirmatory measurement model analysis in PLS-SEM. Indicator factor loadings exceeding 0.70 demonstrated that the observed variables adequately represented their respective latent constructs.

Convergent Validity

Convergent validity was evaluated using the Average Variance Extracted (AVE). AVE values above 0.50 confirmed that each construct explained more than half of the variance in its indicators.

Discriminant Validity

Discriminant validity was assessed using both the Fornell–Larcker Criterion and the Heterotrait–Monotrait Ratio (HTMT). HTMT values below 0.85 indicated satisfactory discriminant validity among the study constructs.

Common Method Bias

To minimize common method bias, respondent anonymity was ensured, questionnaire items were carefully worded and arranged, and Harman's single-factor test was conducted to verify that common method variance did not significantly affect the results.

Data Analysis Technique

The collected data were coded, cleaned, and analyzed using the Statistical Package for the Social Sciences (SPSS) for descriptive statistics and preliminary analysis. SmartPLS 4 was employed to evaluate the measurement and structural models using Partial Least Squares Structural Equation Modeling (PLS-SEM). The analysis included descriptive statistics, reliability assessment, validity testing, correlation analysis, hypothesis testing, mediation analysis, coefficient of determination (R^2), effect size (f^2), predictive relevance (Q^2), and model fit evaluation.

Data Analysis

Respondents' Demographic Profile

Table 1: Demographic Characteristics of Respondents (N = 400)

Variable	Category	Frequency	Percentage (%)
Gender	Male	278	69.5
	Female	122	30.5
Profession	Agricultural Scientists	112	28.0
	Plant Breeders	64	16.0
	University Researchers	78	19.5
	Extension Officers	74	18.5
	Progressive Farmers	72	18.0
Experience	Below 5 Years	96	24.0
	5–10 Years	178	44.5
	Above 10 Years	126	31.5

The study included 400 respondents representing diverse agricultural and biotechnology stakeholders. Agricultural scientists constituted the largest group (28.0%), followed by university researchers (19.5%), extension officers (18.5%), progressive farmers (18.0%), and plant breeders (16.0%). Nearly half (44.5%) possessed between 5 and 10 years of professional experience, indicating that the respondents had sufficient expertise to evaluate CRISPR technology and sustainable agriculture.

Descriptive Statistics

Table 2 : Descriptive Statistics

Construct	Mean	SD	Skewness	Kurtosis
CRISPR-Based Climate-Resilient Crop Improvement	4.18	0.61	-0.48	-0.41
Climate Resilience	4.05	0.65	-0.37	-0.28
Sustainable Agriculture	4.12	0.58	-0.42	-0.35

Respondents expressed favorable perceptions regarding CRISPR-based climate-resilient crop improvement (M = 4.18), climate resilience (M = 4.05), and sustainable agriculture (M = 4.12). Skewness and kurtosis values fell within the acceptable range (±2), indicating that the data approximated a normal distribution and were suitable for multivariate analysis.

Reliability Analysis

Table 3 : Reliability Statistics

Construct	Cronbach's Alpha	Composite Reliability
CRISPR-Based Climate-Resilient Crop Improvement	0.931	0.942
Climate Resilience	0.918	0.930
Sustainable Agriculture	0.926	0.938

All constructs demonstrated excellent internal consistency. Cronbach's Alpha values ranged from 0.918 to 0.931, while Composite Reliability values ranged from 0.930 to 0.942, exceeding the recommended threshold of 0.70. These findings confirmed the reliability of the measurement scales.

Convergent Validity

Table 4: Convergent Validity

Construct	Factor Loading Range	AVE
CRISPR-Based Climate-Resilient Crop Improvement	0.77–0.92	0.73
Climate Resilience	0.75–0.91	0.71
Sustainable Agriculture	0.78–0.93	0.74

All factor loadings exceeded 0.70, while AVE values ranged from 0.71 to 0.74, confirming satisfactory convergent validity. The measurement indicators adequately represented their respective latent constructs.

Correlation Analysis

Table 5 : Correlation Matrix

Variable	1	2	3
CRISPR-Based Crop Improvement	1		
Climate Resilience	0.694**	1	
Sustainable Agriculture	0.721**	0.748**	1

Note. p < .01.

The correlation analysis revealed strong positive relationships among all study variables. CRISPR-Based Crop Improvement was significantly associated with Climate Resilience ($r = 0.694$, $p < .01$) and Sustainable Agriculture ($r = 0.721$, $p < .01$). Furthermore, Climate Resilience demonstrated a strong positive association with Sustainable Agriculture ($r = 0.748$, $p < .01$), indicating that improved resilience contributes substantially to sustainable agricultural development.

Structural Model Results

Table 6 : Hypothesis Testing

Hypothesis	Structural Path	β	t-value	p-value	Decision
H1	CRISPR-Based Crop Improvement → Sustainable Agriculture	0.426	8.95	<0.001	Supported
H2	CRISPR-Based Crop Improvement → Climate Resilience	0.672	15.27	<0.001	Supported
H3	Climate Resilience → Sustainable Agriculture	0.411	8.63	<0.001	Supported

The structural model indicated that CRISPR-Based Climate-Resilient Crop Improvement exerted a significant positive influence on Sustainable Agriculture ($\beta = 0.426$, $p < .001$), supporting H1. It also significantly enhanced Climate Resilience ($\beta = 0.672$, $p < .001$), confirming H2. In addition, Climate Resilience positively affected Sustainable Agriculture ($\beta = 0.411$, $p < .001$), supporting H3. These findings suggest that CRISPR technology contributes directly to sustainable agriculture while simultaneously strengthening crops' capacity to withstand climate-induced stresses.

Mediation Analysis

Table 7 : Indirect Effect

Hypothesis	Indirect Path	β	t-value	p-value	Decision
H4	CRISPR-Based Crop Improvement → Climate Resilience → Sustainable Agriculture	0.276	6.84	<0.001	Supported

The mediation analysis confirmed that Climate Resilience significantly mediated the relationship between CRISPR-Based Climate-Resilient Crop Improvement and Sustainable Agriculture ($\beta = 0.276$, $p < .001$). This finding indicates that CRISPR technology enhances sustainable agriculture not only through direct improvements in crop performance but also by increasing the resilience of crops to climate-related stresses.

Coefficient of Determination (R^2)

Table 8: Coefficient of Determination

Endogenous Variable	R^2	Interpretation
Climate Resilience	0.452	Moderate
Sustainable Agriculture	0.641	Substantial

The coefficient of determination showed that CRISPR-Based Crop Improvement explained 45.2% of the variance in Climate Resilience, while CRISPR-Based Crop Improvement and Climate

Resilience jointly explained 64.1% of the variance in Sustainable Agriculture. These values indicate that the proposed model possesses substantial explanatory power.

Summary of Hypothesis Testing

Table 9 : Summary of Hypotheses

Hypothesis	Statement	Result
H1	CRISPR-Based Climate-Resilient Crop Improvement positively affects Sustainable Agriculture.	Supported
H2	CRISPR-Based Climate-Resilient Crop Improvement positively affects Climate Resilience.	Supported
H3	Climate Resilience positively affects Sustainable Agriculture.	Supported
H4	Climate Resilience mediates the relationship between CRISPR-Based Climate-Resilient Crop Improvement and Sustainable Agriculture.	Supported

The findings demonstrate that CRISPR-Based Climate-Resilient Crop Improvement is a significant driver of Sustainable Agriculture in Pakistan. The technology enables the development of crop varieties with enhanced tolerance to drought, heat, salinity, flooding, and diseases, thereby improving agricultural productivity under changing climatic conditions. The results further reveal that Climate Resilience plays a crucial mediating role by strengthening the ability of crops to adapt to environmental stresses, which subsequently enhances long-term agricultural sustainability. Overall, the findings support Sustainable Agricultural Innovation Theory, suggesting that strategic investment in CRISPR research, biotechnology infrastructure, regulatory frameworks, and capacity building can accelerate climate adaptation, improve food security, reduce environmental impacts, and promote sustainable agricultural development in Pakistan.

Discussion

The findings of this study demonstrated that CRISPR-Based Climate-Resilient Crop Improvement significantly contributes to Sustainable Agriculture in Pakistan. The results revealed that the application of CRISPR genome-editing technology enhances crop productivity, improves tolerance to climate-induced stresses, and supports environmentally sustainable agricultural practices. These findings are consistent with Sustainable Agricultural Innovation Theory, which posits that advanced agricultural technologies play a critical role in improving food security, climate adaptation, and long-term agricultural sustainability (Food and Agriculture Organization [FAO], 2023).

The study found a significant positive relationship between CRISPR-Based Crop Improvement and Sustainable Agriculture, indicating that precise genome editing enables the development of crop varieties with enhanced yield, resource-use efficiency, and resistance to pests and diseases. These findings are consistent with previous studies reporting that CRISPR technology accelerates crop improvement while reducing dependence on chemical fertilizers and pesticides, thereby contributing to environmentally sustainable farming systems (Gao, 2021; Chen et al., 2024).

The results further demonstrated that CRISPR-Based Crop Improvement significantly enhances Climate Resilience. Genome-edited crops possessing improved tolerance to drought, heat, salinity, flooding, and emerging plant pathogens are better equipped to maintain stable productivity under adverse climatic conditions. This finding aligns with recent evidence suggesting that CRISPR technology has become one of the most promising approaches for accelerating climate adaptation in agriculture through precise modification of stress-responsive genes (Zsögön et al., 2022).

The study also established that Climate Resilience positively influences Sustainable Agriculture, indicating that crops capable of withstanding environmental stresses contribute to improved agricultural productivity, efficient resource utilization, and long-term food security. Enhanced resilience reduces production risks, stabilizes farm income, conserves natural resources, and supports sustainable agricultural development under increasingly variable climatic conditions.

Furthermore, the mediation analysis confirmed that Climate Resilience partially mediates the relationship between CRISPR-Based Climate-Resilient Crop Improvement and Sustainable Agriculture. This finding suggests that CRISPR technology strengthens sustainable agriculture not only through direct genetic improvements but also by increasing crops' adaptive capacity to climate change. Consequently, integrating genome-editing technologies into national agricultural strategies can significantly enhance Pakistan's resilience to climate change while promoting sustainable food production.

Conclusion

This study examined the role of CRISPR-Based Climate-Resilient Crop Improvement in promoting Sustainable Agriculture in Pakistan. The findings confirmed that CRISPR genome-editing technology significantly improves agricultural sustainability by enhancing crop productivity, strengthening resistance to climate-induced stresses, and increasing resource-use efficiency.

The study further established that Climate Resilience serves as an important mediating mechanism through which CRISPR technology contributes to sustainable agricultural development. Climate-resilient crops are better able to withstand drought, heat, salinity, floods, pests, and diseases, thereby ensuring more stable agricultural production and improved food security.

Overall, the study concludes that CRISPR-based genome editing represents a transformative agricultural innovation capable of strengthening climate adaptation, improving environmental sustainability, and supporting long-term agricultural development in Pakistan. Strategic investment in biotechnology research, supportive regulatory frameworks, and institutional capacity building will be essential for realizing the full potential of CRISPR technology.

Implications

Theoretical Implications

The study contributes to the literature by extending Sustainable Agricultural Innovation Theory to explain the role of CRISPR genome editing in climate-resilient agriculture. It provides empirical evidence that climate resilience functions as a key mechanism linking biotechnology innovation with sustainable agricultural outcomes. The proposed framework enriches research on agricultural biotechnology, climate adaptation, and sustainable development in emerging economies.

Practical Implications

The findings provide valuable guidance for agricultural scientists, plant breeders, biotechnology researchers, universities, and agricultural extension organizations. Greater investment in CRISPR research, genome-editing laboratories, and advanced breeding programs can accelerate the development of climate-resilient crop varieties. Capacity-building initiatives and technical training for researchers and extension professionals can further facilitate the adoption of genome-editing technologies.

Policy Implications

The findings offer important evidence for government agencies, biotechnology regulators, and agricultural policymakers. Policymakers should strengthen national biotechnology strategies by increasing research funding, developing science-based regulatory frameworks for genome-edited crops, promoting public-private partnerships, and encouraging collaboration among universities, research institutes, and the agricultural industry. Such initiatives will enhance climate adaptation, food security, and sustainable agricultural development in Pakistan.

Recommendations

Based on the findings, the following recommendations are proposed:

- The Government of Pakistan should increase investment in CRISPR research, agricultural biotechnology, and modern genome-editing laboratories.
- Agricultural research institutions should accelerate the development of climate-resilient crop varieties with enhanced tolerance to drought, heat, salinity, flooding, pests, and diseases.
- Science-based regulatory frameworks should be established to facilitate the safe evaluation, approval, and commercialization of genome-edited crops.
- Stronger collaboration should be promoted among universities, biotechnology research centers, agricultural industries, and international research organizations to accelerate technology transfer and innovation.
- Specialized training programs should be introduced to develop expertise in genome editing, molecular breeding, bioinformatics, and precision agriculture.
- Public awareness initiatives should be implemented to improve understanding of CRISPR technology, address ethical and biosafety concerns, and increase public acceptance of genome-edited crops.
- CRISPR technology should be integrated with complementary innovations such as artificial intelligence, precision agriculture, genomic selection, remote sensing, and digital farming systems to maximize agricultural productivity and climate resilience.

Limitations and Future Directions

This study has several limitations. First, the cross-sectional research design limited the ability to establish causal relationships among CRISPR-based crop improvement, climate resilience, and sustainable agriculture over time. Future studies should employ longitudinal designs to examine the long-term impacts of genome-editing technologies on agricultural sustainability.

Second, the study relied on self-reported survey data, which may be subject to respondent bias and common method variance. Future research should incorporate experimental studies, field trials, laboratory evaluations, and longitudinal datasets to validate the findings.

Third, the study focused on Pakistan, limiting the generalizability of the results to other agricultural systems. Comparative studies across South Asia and other climate-vulnerable regions would strengthen the external validity of the findings.

Fourth, Climate Resilience was examined as the sole mediating variable. Future studies should investigate additional mediators and moderators, including technology adoption, government support, research and development capacity, farmers' awareness, institutional readiness, regulatory quality, innovation capability, and environmental sustainability practices.

Finally, future research should examine the integration of CRISPR genome editing with emerging technologies such as artificial intelligence, machine learning, digital agriculture, Internet of Things (IoT), genomic selection, phenomics, and precision farming to develop next-generation climate-smart agricultural systems capable of enhancing food security and sustainable agricultural development under rapidly changing climatic conditions.

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