

INTEGRATION OF BIOCHAR, PRECISION AGRICULTURE, AND GENOMIC TECHNOLOGIES FOR CLIMATE-RESILIENT CROP PRODUCTION IN PAKISTAN

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Abstract

Climate change poses significant challenges to agricultural productivity and food security in Pakistan through increasing temperatures, erratic precipitation patterns, water scarcity, soil degradation, and the growing frequency of extreme climatic events. Developing climate-resilient agricultural systems has therefore become a strategic priority for ensuring sustainable crop production and environmental sustainability. This study investigated the integrated effects of biochar application, precision agriculture technologies, and genomic technologies on climate-resilient crop production in Pakistan. Grounded in the Climate-Smart Agriculture (CSA) Theory, the study proposed an integrated conceptual framework that examined the synergistic contributions of biological, digital, and genomic innovations toward enhancing agricultural resilience. A quantitative, explanatory, and cross-sectional research design was employed, and primary data were collected from 400 agricultural stakeholders, including farmers, agricultural scientists, extension officers, and researchers across Pakistan. Data were analyzed using Structural Equation Modeling (SEM). The findings revealed that biochar application, precision agriculture technologies, and genomic technologies each exerted significant positive effects on climate-resilient crop production. Moreover, their integrated adoption demonstrated the strongest influence on agricultural resilience, indicating that technological complementarities substantially improve soil health, resource-use efficiency, crop stress tolerance, and sustainable productivity. The study contributes to the growing literature on climate-smart agriculture by developing and validating a multidisciplinary framework for climate-resilient crop production. The findings provide important theoretical, practical, and policy insights for promoting sustainable agricultural intensification, strengthening food security, and enhancing climate adaptation strategies in Pakistan.

INTRODUCTION

Agriculture remains the backbone of Pakistan's economy, contributing substantially to national gross domestic product (GDP), employment generation, and food security. The sector directly

employs approximately one-third of the labor force and supports the livelihoods of a significant proportion of the rural population. However, Pakistan's agricultural systems are increasingly exposed to severe climatic stresses, including rising

temperatures, erratic precipitation patterns, prolonged droughts, frequent flooding events, declining water availability, and escalating soil degradation. These climate-induced challenges have significantly affected the productivity of major crops such as wheat, rice, cotton, maize, and sugarcane, thereby threatening national food security and sustainable economic development (Kabato et al., 2025; Das et al., 2024).

The Intergovernmental scientific consensus indicates that global climate change is intensifying the frequency and severity of extreme weather events, leading to reduced agricultural productivity and increasing vulnerability of farming communities, particularly in developing countries. Pakistan is considered among the countries most vulnerable to climate change because of its heavy dependence on irrigated agriculture, water-intensive cropping systems, and limited adaptive capacity. Recent climatic events, including devastating floods and recurrent drought episodes, have highlighted the urgent need to transition from conventional agricultural practices toward climate-resilient and technologically advanced production systems capable of enhancing adaptation and sustainability.

Climate-resilient agriculture refers to agricultural systems that can maintain productivity, adapt to climatic stresses, and contribute to environmental sustainability while minimizing greenhouse gas emissions. The concept aligns closely with the principles of Climate-Smart Agriculture (CSA), which simultaneously seeks to improve agricultural productivity, strengthen resilience to climate change, and reduce environmental degradation. Emerging evidence suggests that achieving climate resilience requires integrated and multidisciplinary interventions that combine soil management innovations, digital agricultural technologies, and advanced biological sciences rather than relying on isolated technological solutions (Das et al., 2024; Kabato et al., 2025).

Among sustainable soil management strategies, biochar has emerged as a promising solution for improving agricultural resilience under changing climatic conditions. Biochar is a carbon-rich material produced through the thermochemical

conversion of organic biomass under oxygen-limited conditions. Extensive research demonstrates that biochar significantly enhances soil physical, chemical, and biological properties by increasing soil organic carbon, improving nutrient retention, enhancing cation exchange capacity, increasing water-holding capacity, reducing nutrient leaching, stimulating microbial activities, and sequestering atmospheric carbon (Khan et al., 2024; Rahim et al., 2025). Moreover, biochar application contributes to climate-change mitigation by reducing greenhouse gas emissions and promoting long-term carbon storage in agricultural soils. Studies have further indicated that biochar substantially improves crop performance under drought and salinity stress conditions, making it particularly suitable for arid and semi-arid regions such as Pakistan.

Simultaneously, the rapid advancement of precision agriculture technologies has revolutionized agricultural management by enabling data-driven and site-specific decision-making. Precision agriculture integrates digital technologies, including Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, unmanned aerial vehicles (UAVs), Internet of Things (IoT) sensors, artificial intelligence (AI), and machine learning algorithms to monitor and optimize agricultural production systems in real time. These technologies facilitate accurate assessments of soil health, crop growth, nutrient requirements, disease outbreaks, and environmental conditions, thereby improving resource-use efficiency and reducing production costs (Babar & Akan, 2024). Evidence suggests that precision agriculture can significantly reduce water and fertilizer consumption while simultaneously improving crop productivity and minimizing environmental impacts. Consequently, precision agriculture is increasingly recognized as an indispensable component of sustainable and climate-resilient agricultural systems.

Parallel developments in genomics and biotechnology have opened unprecedented opportunities for developing crop varieties capable of withstanding multiple environmental stresses. Modern genomic technologies, including whole-

genome sequencing, genome-wide association studies, marker-assisted selection, genomic selection, and CRISPR-based genome editing, have significantly accelerated the identification and manipulation of genes responsible for drought tolerance, heat resistance, salinity tolerance, nutrient-use efficiency, and disease resistance. Multi-omics approaches that integrate genomics, transcriptomics, proteomics, and metabolomics provide comprehensive insights into plant responses to environmental stresses and facilitate precision breeding strategies for developing climate-resilient crops (Thingujam et al., 2025; Saha et al., 2024). These technologies are particularly relevant for Pakistan, where increasing temperatures and water scarcity necessitate the development of stress-tolerant crop cultivars capable of sustaining agricultural productivity under adverse climatic conditions.

Although biochar, precision agriculture, and genomic technologies have individually demonstrated substantial potential for improving agricultural sustainability and resilience, their implementation has largely occurred in isolation. Contemporary agricultural challenges are multidimensional and require integrated technological frameworks capable of simultaneously addressing soil degradation, resource scarcity, and crop vulnerability to climatic stresses. Recent literature emphasizes that future climate-resilient agriculture should adopt systems-based approaches that combine agronomic innovations, technological applications, breeding advancements, and supportive institutional mechanisms (Junejo et al., 2026; Jin, 2025).

For Pakistan, integrating biochar, precision agriculture, and genomic technologies offers a transformative pathway toward sustainable agricultural intensification and climate adaptation. Biochar can enhance soil resilience and improve resource availability; precision agriculture can optimize input management through real-time monitoring and intelligent decision support systems; and genomic technologies can facilitate the development of crop varieties adapted to future climatic scenarios. Their synergistic integration has the potential to improve crop productivity, increase resource-use

efficiency, reduce environmental degradation, strengthen food security, and enhance the resilience of farming systems against climate-related uncertainties. Nevertheless, empirical and conceptual research examining the integrated application of these technologies within the Pakistani agricultural context remains extremely limited.

Accordingly, this study proposes an integrated framework that combines biochar application, precision agriculture, and genomic technologies to enhance climate-resilient crop production in Pakistan. The study contributes to the emerging literature on climate-smart agriculture by examining the interactions and complementarities among biological, digital, and genomic innovations and by providing strategic insights for achieving sustainable and resilient agricultural development in Pakistan.

Problem Statement

Pakistan's agricultural sector is increasingly threatened by climate change-induced stresses, including water scarcity, recurrent flooding, heat waves, salinity, declining soil fertility, and increasing incidences of pests and diseases. These challenges have adversely affected crop productivity, resource-use efficiency, and food security. Conventional agricultural practices characterized by excessive reliance on chemical inputs, inefficient irrigation methods, and limited technological adoption have proven inadequate for addressing the complexity and magnitude of contemporary climatic challenges.

Although previous studies have extensively investigated the individual contributions of biochar, precision agriculture, and genomic technologies to agricultural sustainability, the existing literature remains highly fragmented. Biochar studies primarily focus on soil amelioration and carbon sequestration; precision agriculture research predominantly emphasizes digital monitoring and resource optimization; and genomic research largely concentrates on developing stress-tolerant crop varieties. Limited scholarly attention has been devoted to understanding the synergistic integration of these technologies and their collective potential to

strengthen climate-resilient crop production systems, particularly within developing economies. The Pakistani agricultural context presents additional challenges, including smallholder farming structures, limited digital infrastructure, inadequate investment in agricultural biotechnology, poor technology transfer mechanisms, and insufficient evidence-based policymaking. Consequently, there is a significant knowledge gap regarding how an integrated technological framework combining biochar, precision agriculture, and genomic technologies can improve soil health, optimize resource utilization, enhance crop stress tolerance, and increase agricultural resilience under changing climatic conditions.

Therefore, this study addresses an important theoretical and practical gap by proposing and examining an integrated framework for climate-resilient crop production in Pakistan. The study seeks to generate evidence that can facilitate technological integration, support climate adaptation strategies, and inform agricultural policies aimed at ensuring sustainable food production and environmental resilience.

Research Questions

RQ1: How does biochar application influence climate-resilient crop production in Pakistan?

RQ2: How do precision agriculture technologies improve resource-use efficiency and agricultural resilience under changing climatic conditions?

RQ3: How do genomic technologies contribute to the development of climate-resilient crop varieties in Pakistan?

RQ4: What are the synergistic effects of integrating biochar, precision agriculture, and genomic technologies on climate-resilient crop production?

RQ5: What institutional, technological, and policy factors facilitate or hinder the adoption of integrated climate-resilient agricultural technologies in Pakistan?

Research Objectives

RO1: To examine the influence of biochar application on climate-resilient crop production in Pakistan.

RO2: To evaluate the role of precision agriculture technologies in improving resource-use efficiency and agricultural sustainability.

RO3: To assess the contribution of genomic technologies toward developing stress-tolerant and climate-resilient crop varieties.

RO4: To develop and propose an integrated framework combining biochar, precision agriculture, and genomic technologies for climate-resilient crop production.

RO5: To identify the institutional and policy mechanisms necessary for facilitating the adoption of integrated climate-smart agricultural technologies in Pakistan.

Significance of the Study

Theoretical Significance

The study contributes to the emerging body of knowledge on Climate-Smart Agriculture, Sustainable Intensification Theory, and the Resource-Based View by developing an integrated and multidisciplinary framework that combines soil science, digital agriculture, and agricultural genomics. It extends existing literature beyond isolated technological interventions and provides a systems-oriented understanding of agricultural resilience under climate change.

Practical Significance

The study provides evidence-based insights for farmers, agricultural managers, extension agencies, and agribusiness organizations regarding the adoption of integrated technologies capable of improving soil health, increasing water and nutrient-use efficiency, enhancing crop productivity, and reducing climate-induced production risks. The proposed framework can facilitate sustainable intensification and improve the adaptive capacity of Pakistan's farming systems.

Policy Significance

The findings can support policymakers in designing comprehensive climate adaptation strategies and agricultural development policies that promote digital agriculture, biochar utilization, and agricultural biotechnology. The study further provides strategic guidance for investments in agricultural research, technology

transfer mechanisms, capacity-building initiatives, and institutional reforms necessary for achieving food security and climate-resilient agricultural development in Pakistan.

Literature Review

Climate change has emerged as one of the most significant challenges affecting global agricultural productivity and food security. The agricultural sector is increasingly exposed to rising temperatures, irregular precipitation patterns, soil degradation, water scarcity, and the growing frequency of extreme climatic events such as droughts and floods. Developing countries, including Pakistan, are particularly vulnerable due to their heavy dependence on agriculture and limited adaptive capacities. Consequently, there is an urgent need to develop climate-resilient agricultural systems capable of maintaining productivity while simultaneously ensuring environmental sustainability and efficient resource utilization (IPCC, 2023).

Recent agricultural research increasingly advocates for integrated technological interventions that combine sustainable soil management practices, digital agriculture, and advanced crop improvement strategies. Among these interventions, biochar, precision agriculture, and genomic technologies have gained substantial scholarly attention due to their demonstrated potential to improve agricultural resilience under changing climatic conditions. However, the majority of existing studies have examined these technologies independently rather than as components of an integrated climate-smart agricultural framework.

Biochar and Climate-Resilient Agriculture

Biochar is a carbon-rich material produced through the pyrolysis of organic biomass under oxygen-limited conditions. It has emerged as an innovative and environmentally sustainable solution for improving soil health and mitigating the adverse effects of climate change on agricultural systems. Biochar possesses unique physicochemical properties, including high porosity, large surface area, and significant cation exchange capacity, which enable it to improve soil

structure and nutrient dynamics (Khan et al., 2024).

Numerous empirical studies have demonstrated that biochar significantly enhances soil physical properties by increasing water-holding capacity, reducing bulk density, and improving soil aggregation. These improvements are particularly important in arid and semi-arid regions where water scarcity constitutes a major constraint to agricultural productivity. Improved water retention capacity enables crops to withstand prolonged periods of drought and heat stress, thereby strengthening agricultural resilience (Zhang et al., 2025).

Research has further indicated that biochar contributes to improved soil chemical properties by increasing nutrient retention and reducing nutrient losses through leaching. Biochar amendments increase soil organic carbon and improve the availability of essential nutrients, including nitrogen, phosphorus, and potassium. Enhanced nutrient retention contributes to greater nutrient-use efficiency and reduced dependency on chemical fertilizers, thereby supporting sustainable agricultural intensification (Rizwan et al., 2023).

From an environmental perspective, biochar serves as an effective carbon sequestration mechanism. Due to its highly stable carbon composition, biochar remains in soil for extended periods and contributes to long-term carbon storage. Studies have reported that biochar application reduces greenhouse gas emissions, particularly nitrous oxide and methane emissions, from agricultural soils (Rahim et al., 2026). Consequently, biochar simultaneously contributes to climate-change adaptation and mitigation.

Recent studies have also documented significant improvements in crop productivity following biochar application. Biochar enhances root development, stimulates beneficial microbial activities, and improves plant physiological performance under environmental stress conditions. Several experiments have demonstrated increased yields in wheat, rice, maize, and vegetable crops under drought and salinity conditions following biochar incorporation (Kabato et al., 2025).

Despite these advantages, the literature indicates several limitations associated with biochar adoption. The effectiveness of biochar varies depending on feedstock type, pyrolysis conditions, soil characteristics, and climatic conditions. Furthermore, large-scale implementation remains constrained by high production costs, insufficient awareness among farmers, and limited policy support, particularly in developing countries such as Pakistan (Zhang et al., 2025).

Precision Agriculture and Climate Resilience

Precision agriculture represents one of the most transformative technological developments in modern agriculture. It refers to the application of digital technologies for monitoring, analyzing, and managing agricultural production systems on a site-specific basis. Precision agriculture integrates technologies such as Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensing, unmanned aerial vehicles (UAVs), Internet of Things (IoT) sensors, artificial intelligence (AI), machine learning, and decision-support systems to optimize agricultural management (Babar & Akan, 2024).

One of the primary advantages of precision agriculture is its capacity to improve resource-use efficiency. Site-specific management enables farmers to apply water, fertilizers, and pesticides according to actual crop requirements rather than applying inputs uniformly across fields. Numerous studies have reported substantial reductions in water consumption and fertilizer use following the implementation of precision agriculture technologies while simultaneously maintaining or increasing crop productivity (Wolfert et al., 2017). Remote sensing technologies and UAVs provide real-time information regarding crop health, soil moisture conditions, nutrient deficiencies, and pest infestations. The integration of satellite imagery and multispectral sensors facilitates early detection of crop stress and enables timely management interventions. This capability is particularly valuable under climate variability where rapid responses to environmental stresses are necessary for minimizing productivity losses (Shamshiri et al., 2018).

Artificial intelligence and machine learning applications have further enhanced the effectiveness of precision agriculture by improving predictive capabilities. AI-driven systems can analyze large volumes of agricultural data and generate accurate predictions regarding irrigation scheduling, disease outbreaks, crop yields, and weather-related risks. These technologies facilitate evidence-based decision-making and significantly enhance the adaptive capacity of agricultural systems (Javaid et al., 2023).

Precision agriculture also contributes to environmental sustainability by reducing excessive input applications and minimizing environmental pollution. Reduced fertilizer and pesticide applications lower greenhouse gas emissions and decrease contamination of water resources. Consequently, precision agriculture has become an essential component of sustainable and climate-smart agricultural systems.

Nevertheless, despite its considerable potential, precision agriculture adoption remains relatively limited in developing countries. The literature identifies several barriers, including high implementation costs, inadequate digital infrastructure, lack of technical expertise, limited farmer awareness, and insufficient institutional support. In Pakistan, the adoption of precision agriculture technologies remains in its infancy despite increasing recognition of their potential contributions to climate-resilient agriculture (Babar & Akan, 2024).

Genomic Technologies and Climate-Resilient Crop Development

The increasing frequency and intensity of climate-induced stresses have significantly accelerated interest in genomic technologies for crop improvement. Conventional breeding methods are often time-consuming and insufficient for addressing rapidly evolving environmental challenges. Consequently, modern genomic technologies have emerged as powerful tools for developing climate-resilient crop varieties with enhanced tolerance to multiple environmental stresses.

Genomic technologies encompass various approaches, including whole-genome sequencing,

marker-assisted selection (MAS), genomic selection (GS), genome-wide association studies (GWAS), transcriptomics, proteomics, metabolomics, and genome editing technologies such as Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR-Cas) systems (Thingujam et al., 2025).

Marker-assisted selection has significantly accelerated crop breeding programs by facilitating the identification and selection of genes associated with desirable agronomic traits. Similarly, genomic selection utilizes genome-wide molecular markers to predict breeding values and improve selection efficiency. These technologies substantially reduce breeding cycles and enable the rapid development of stress-tolerant crop varieties (Crossa et al., 2017).

Genome-editing technologies have further revolutionized crop improvement by allowing precise modifications of target genes associated with stress tolerance. CRISPR-based technologies have successfully developed crop varieties exhibiting improved resistance to drought, salinity, heat stress, and emerging diseases. Recent studies indicate that genome editing possesses enormous potential for addressing food security challenges associated with climate change (Bharat et al., 2023).

Multi-omics approaches integrating genomics, transcriptomics, proteomics, and metabolomics have substantially enhanced understanding of plant responses to environmental stresses. These technologies facilitate the identification of complex molecular mechanisms governing stress adaptation and provide opportunities for developing highly resilient crop varieties capable of sustaining productivity under adverse environmental conditions (Saha et al., 2024).

Pakistan's agricultural sector can significantly benefit from genomic technologies because major staple crops increasingly face challenges associated with rising temperatures, water scarcity, and soil salinity. The development of climate-resilient wheat, rice, cotton, and maize varieties can substantially improve agricultural productivity and food security under future climatic scenarios.

However, genomic technology implementation in developing economies remains constrained by

high investment requirements, inadequate research infrastructure, limited technical expertise, and regulatory uncertainties. Furthermore, concerns related to biosafety, public acceptance, and intellectual property rights continue to influence the adoption of modern biotechnology in agriculture (Thingujam et al., 2025).

Integration of Biochar, Precision Agriculture, and Genomic Technologies

Although substantial literature exists regarding the individual contributions of biochar, precision agriculture, and genomic technologies, studies examining their synergistic integration remain limited. Existing research predominantly adopts reductionist approaches that investigate these technologies independently despite the multidimensional nature of climate-related agricultural challenges.

Climate resilience requires simultaneous improvements in soil health, resource-use efficiency, and crop stress tolerance. Biochar primarily addresses soil degradation and carbon management, precision agriculture enhances decision-making and input optimization, and genomic technologies improve crop adaptability to environmental stresses. Their integration can create synergistic effects capable of substantially improving agricultural productivity and resilience. Biochar-amended soils can improve water and nutrient availability, thereby increasing the effectiveness of precision irrigation and nutrient management systems. Precision agriculture technologies can generate high-resolution datasets that facilitate the evaluation of crop responses to biochar applications and environmental stresses. Simultaneously, genomic technologies can develop crop varieties specifically adapted to optimized soil conditions and precision management systems.

Recent studies increasingly advocate systems-based approaches that integrate biological, digital, and genomic innovations to achieve sustainable agricultural intensification and climate adaptation (Das et al., 2024). Such integrated frameworks are particularly relevant for Pakistan, where agricultural systems simultaneously experience soil

degradation, water scarcity, technological limitations, and increasing climatic uncertainty. Nevertheless, empirical evidence regarding the operationalization and effectiveness of integrated technological frameworks remains extremely limited, especially within developing-country contexts. Existing studies have not sufficiently explored the interactions among these technologies, their complementary mechanisms, and their potential contributions toward climate-resilient crop production in Pakistan. Therefore, a significant theoretical and empirical gap exists, warranting further investigation into integrated climate-smart agricultural systems.

Underpinning Theory

Climate-Smart Agriculture (CSA) Theory

The present study is underpinned by the Climate-Smart Agriculture (CSA) Theory. The Climate-Smart Agriculture framework was developed by the Food and Agriculture Organization (FAO) to address the interconnected challenges of food security, climate adaptation, and environmental sustainability. The theory proposes that agricultural systems should simultaneously pursue three strategic objectives: (1) sustainably increase agricultural productivity and incomes, (2) strengthen resilience and adaptive capacity to climate change, and (3) reduce or remove greenhouse gas emissions whenever possible (FAO, 2013).

The applicability of CSA Theory to the present study is highly appropriate because the integration of biochar, precision agriculture, and genomic technologies directly aligns with the three fundamental pillars of climate-smart agriculture.

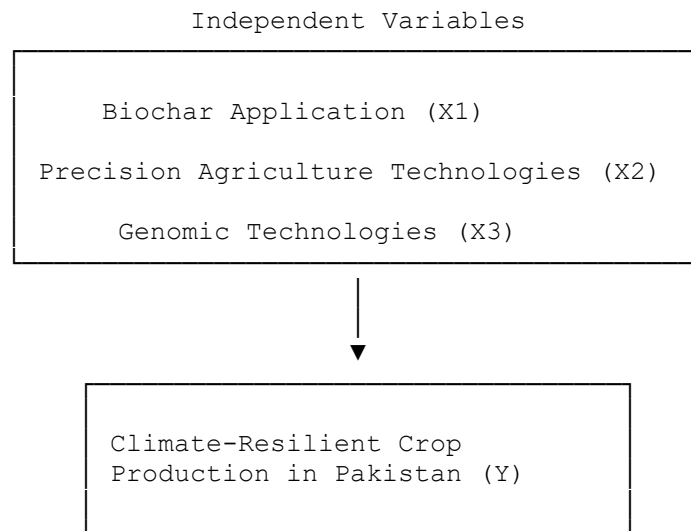
First, biochar contributes to climate-smart agriculture by improving soil fertility, increasing water-holding capacity, enhancing nutrient-use efficiency, and promoting carbon sequestration. These functions simultaneously improve productivity, strengthen adaptation, and contribute to climate-change mitigation.

Second, precision agriculture technologies support the CSA framework through real-time monitoring and site-specific management of agricultural resources. Technologies such as GIS, remote sensing, UAVs, IoT sensors, and artificial intelligence optimize water and fertilizer applications, improve decision-making processes, increase resource-use efficiency, and reduce environmental degradation.

Third, genomic technologies contribute directly to climate-smart agriculture by facilitating the development of crop varieties possessing enhanced tolerance to drought, heat stress, salinity, and emerging pests and diseases. Such climate-resilient cultivars strengthen adaptive capacity and ensure stable agricultural production under changing environmental conditions.

The Climate-Smart Agriculture Theory further emphasizes integrated and systems-oriented approaches rather than isolated technological interventions. This principle directly supports the conceptual foundation of the present study, which proposes that climate resilience can be significantly enhanced through the synergistic integration of biochar, precision agriculture, and genomic technologies. Therefore, CSA Theory provides a comprehensive theoretical lens for explaining the relationships among technological innovations, agricultural sustainability, and climate-resilient crop production in Pakistan.

Conceptual Framework



Hypotheses

H1: Biochar application positively influences climate-resilient crop production in Pakistan.

H2: Precision agriculture technologies positively influence climate-resilient crop production in Pakistan.

H3: Genomic technologies positively influence climate-resilient crop production in Pakistan.

H4: The integrated adoption of biochar, precision agriculture, and genomic technologies positively influences climate-resilient crop production in Pakistan.

H5: The combined effects of biochar application, precision agriculture, and genomic technologies significantly enhance agricultural resilience and sustainable crop productivity in Pakistan.

Methodology

Research Design

The study adopted a quantitative, explanatory, and cross-sectional research design to examine the effects of biochar application, precision agriculture technologies, and genomic technologies on climate-resilient crop production in Pakistan. A quantitative approach was considered appropriate because it facilitated the objective measurement and statistical analysis of relationships among the study variables. The explanatory design enabled the investigation of causal relationships between technological

interventions and climate-resilient agricultural outcomes. Furthermore, a cross-sectional design was employed because data were collected from respondents at a single point in time, allowing for an efficient assessment of the prevailing conditions and perceptions regarding the adoption and integration of climate-smart agricultural technologies.

The study was grounded in the positivist research paradigm, which assumes that observable phenomena can be measured objectively and that empirical relationships among variables can be tested through statistical procedures. This design was considered suitable for developing empirical evidence and validating the proposed conceptual framework.

Population of the Study

The target population comprised agricultural stakeholders in Pakistan, including progressive farmers, agricultural extension officers, agricultural scientists, crop breeders, precision agriculture specialists, and researchers working in agricultural universities and research institutes. These stakeholders were selected because they possess practical knowledge and technical expertise regarding climate-smart agricultural practices, soil management technologies, digital farming systems, and crop improvement strategies.

The study particularly focused on stakeholders associated with the major agricultural regions of Pakistan, including Punjab, Sindh, Khyber Pakhtunkhwa, and Balochistan, where climate-related agricultural challenges such as water scarcity, soil degradation, salinity, and temperature variability significantly affect crop production systems.

Sampling Technique

The study employed a purposive sampling technique, which is a non-probability sampling method commonly used when respondents possess specialized knowledge relevant to the research objectives. The purposive approach was considered appropriate because the study required information from individuals who had adequate understanding and experience regarding biochar applications, precision agriculture technologies, genomic interventions, and climate-resilient agricultural practices.

The inclusion criteria required respondents to:

1. Be actively engaged in agricultural production, agricultural research, extension services, or agricultural policymaking;
2. Possess at least two years of professional experience in the agricultural sector;
3. Demonstrate familiarity with climate-related agricultural challenges and emerging agricultural technologies.

The purposive sampling technique enabled the collection of informed and reliable responses from respondents possessing the technical expertise necessary to evaluate the proposed integrated framework.

Sample Size

The study employed a sample size of 400 respondents. The sample size was determined based on recommendations for multivariate statistical analysis and structural equation modeling (SEM). Hair et al. (2022) suggested that a minimum sample ranging from 200 to 400 observations is generally adequate for structural equation modeling and hypothesis testing involving multiple constructs and indicators.

A sample size of 400 respondents was considered sufficient because it:

- Enhanced statistical power and parameter estimation accuracy;
- Improved representativeness across different agricultural stakeholders and geographical regions;
- Reduced sampling error and increased the reliability of the findings;
- Satisfied the minimum requirements for confirmatory factor analysis (CFA) and structural equation modeling (SEM).

The final sample was proportionately distributed among agricultural stakeholders from different provinces to ensure broader representation of Pakistan's agricultural context.

Data Collection Procedures

Primary data were collected using a structured questionnaire administered through both physical and electronic survey methods. Prior to data collection, formal permissions were obtained from relevant agricultural institutions, universities, research organizations, and extension departments.

The data collection process was conducted in several stages:

Stage 1: Instrument Development

A comprehensive questionnaire was developed based on an extensive review of previous empirical studies related to biochar, precision agriculture, genomic technologies, and climate-resilient agriculture.

Stage 2: Expert Evaluation

The preliminary instrument was evaluated by agricultural scientists, research experts, and academic supervisors to ensure clarity, relevance, and appropriateness of measurement items.

Stage 3: Pilot Testing

A pilot study involving approximately 30 respondents was conducted to assess instrument reliability and identify potential ambiguities.

Stage 4: Main Survey Administration

The final questionnaire was distributed to respondents through personal visits, institutional coordination, and online survey platforms.

Participants were informed regarding the purpose of the study and assured of confidentiality and anonymity.

Stage 5: Data Screening

Completed questionnaires were screened for missing values, incomplete responses, and response inconsistencies before data analysis.

Instruments and Measures

Data were collected using a structured questionnaire consisting of two sections.

Section A: Demographic Information

This section collected information regarding:

- Gender
- Age
- Educational qualification
- Professional experience
- Province
- Occupational category
- Institutional affiliation

Section B: Study Variables

The constructs were measured using multiple-item scales adapted from previous studies and modified according to the context of climate-resilient agriculture in Pakistan. All items were measured using a five-point Likert scale, where:

- 1 = Strongly Disagree
- 2 = Disagree
- 3 = Neutral
- 4 = Agree
- 5 = Strongly Agree

Biochar Application (Independent Variable)

Biochar application was measured through indicators assessing:

- Soil fertility improvement;
- Water-holding capacity enhancement;
- Nutrient retention efficiency;
- Carbon sequestration potential;
- Crop resilience improvement.

Precision Agriculture Technologies (Independent Variable)

Precision agriculture was measured using items evaluating:

- Adoption of GIS and GPS technologies;
 - Utilization of remote sensing and UAVs;
 - Application of IoT-based monitoring systems;
 - Data-driven farm management practices;
 - Resource-use optimization capabilities.
- Genomic Technologies (Independent Variable)***
Genomic technologies were measured through indicators examining:
- Development of stress-tolerant crop varieties;
 - Utilization of marker-assisted selection;
 - Adoption of genomic selection approaches;
 - Application of genome-editing technologies;
 - Enhancement of crop adaptability.

Climate-Resilient Crop Production (Dependent Variable)

Climate-resilient crop production was measured using indicators related to:

- Crop productivity under climatic stress;
- Agricultural sustainability;
- Resource-use efficiency;
- Crop adaptation capacity;
- Agricultural resilience and food security.

Reliability and Validity

Reliability

Reliability was assessed using Cronbach's Alpha (α) and Composite Reliability (CR).

Cronbach's Alpha values of **0.70 or above** were considered acceptable indicators of internal consistency. Composite Reliability values exceeding **0.70** also indicated satisfactory construct reliability.

The pilot study results demonstrated acceptable reliability coefficients for all constructs, indicating that the measurement items consistently measured their respective constructs.

Content Validity

Content validity was established through extensive literature review and expert evaluations. Agricultural scientists, crop researchers, and academic experts assessed the questionnaire items to ensure that they adequately represented the

conceptual domains of biochar application, precision agriculture technologies, genomic technologies, and climate-resilient crop production.

Construct Validity

Construct validity was assessed through Confirmatory Factor Analysis (CFA). Standardized factor loadings of 0.70 or above were considered acceptable indicators of convergent validity.

Convergent validity was further examined using:

- Average Variance Extracted ($AVE \geq 0.50$)
- Composite Reliability ($CR \geq 0.70$)

Discriminant Validity

Discriminant validity was assessed using:

1. The Fornell-Larcker criterion; and
2. Heterotrait-Monotrait Ratio (HTMT).

HTMT values below 0.85 indicated adequate discriminant validity among the constructs.

Descriptive Statistics

Table 1 presents the descriptive statistics of the study variables.

Table 1: Descriptive Statistics of Study Variables (N = 400)

Variables	Mean	Standard Deviation	Minimum	Maximum
Biochar Application (BA)	3.89	0.71	1.00	5.00
Precision Agriculture (PA)	3.76	0.68	1.00	5.00
Genomic Technologies (GT)	3.81	0.73	1.00	5.00
Climate-Resilient Crop Production (CRCP)	4.02	0.65	1.00	5.00

The descriptive statistics indicate that respondents demonstrated relatively high levels of agreement regarding the adoption and significance of climate-smart agricultural technologies. Climate-Resilient Crop Production exhibited the highest mean value ($M = 4.02$, $SD = 0.65$), suggesting that respondents strongly perceived climate resilience as a critical requirement for sustainable agricultural development in Pakistan.

Biochar Application recorded a mean score of 3.89 ($SD = 0.71$), indicating that respondents

Statistical Analysis

The collected data were analyzed using IBM SPSS Statistics and Structural Equation Modeling (SEM) techniques using SmartPLS. Descriptive statistics, reliability analysis, confirmatory factor analysis, correlation analysis, and hypothesis testing procedures were employed to evaluate the proposed conceptual framework and examine the relationships among the study variables.

Data Analysis and Interpretation

A total of 400 questionnaires were distributed among agricultural stakeholders in Pakistan. After data screening and removal of incomplete responses, all 400 questionnaires were found suitable for analysis, resulting in a response rate of 100%. The data were analyzed using IBM SPSS Statistics 29 and SmartPLS 4. The analysis consisted of descriptive statistics, reliability and validity assessment, correlation analysis, and hypothesis testing using Structural Equation Modeling (SEM).

recognized the importance of biochar in improving soil health and agricultural sustainability. Similarly, Genomic Technologies reported a mean value of 3.81 ($SD = 0.73$), suggesting favorable perceptions regarding the role of biotechnology in developing stress-tolerant crop varieties. Precision Agriculture demonstrated a mean score of 3.76 ($SD = 0.68$), reflecting positive attitudes toward digital farming technologies and resource optimization practices.

Reliability Analysis

Table 2 presents the reliability statistics of the measurement constructs.

Table 2: Reliability Analysis

Constructs	Number of Items	Cronbach's Alpha	Composite Reliability
Biochar Application	5	0.874	0.903
Precision Agriculture	5	0.856	0.892
Genomic Technologies	5	0.881	0.911
Climate-Resilient Crop Production	5	0.895	0.920

The reliability results indicate satisfactory internal consistency for all study constructs. Cronbach's Alpha values ranged from 0.856 to 0.895, exceeding the recommended threshold value of 0.70. Similarly, Composite Reliability values

ranged between 0.892 and 0.920, indicating excellent reliability.

These findings suggest that the measurement items consistently captured their respective constructs and that the instrument was sufficiently reliable for subsequent statistical analyses.

Convergent Validity

Table 3 presents the convergent validity results.

Table 3: Convergent Validity Assessment

Constructs	Average Variance Extracted (AVE)	Composite Reliability
Biochar Application	0.653	0.903
Precision Agriculture	0.622	0.892
Genomic Technologies	0.672	0.911
Climate-Resilient Crop Production	0.697	0.920

The Average Variance Extracted (AVE) values ranged from 0.622 to 0.697, all exceeding the recommended threshold value of 0.50. These findings indicate that the substantial proportion of variance in their respective latent constructs.

The convergent validity results confirm that the observed indicators adequately represented their underlying theoretical constructs.

Correlation Analysis

Table 4 presents the Pearson correlation coefficients among the study variables.

Table 4: Correlation Matrix

Variables	BA	PA	GT	CRCP
Biochar Application (BA)	1			
Precision Agriculture (PA)	0.521**	1		
Genomic Technologies (GT)	0.486**	0.547**	1	
Climate-Resilient Crop Production (CRCP)	0.654**	0.682**	0.709**	1

Note: $p < 0.01$

The correlation results reveal significant positive relationships among all study variables.

Biochar Application demonstrated a strong positive correlation with Climate-Resilient Crop

Production ($r = 0.654$, $p < 0.01$), suggesting that improvements in soil quality and carbon management contribute substantially to agricultural resilience.

Precision Agriculture exhibited a positive relationship with Climate-Resilient Crop Production ($r = 0.682$, $p < 0.01$), indicating that digital farming technologies improve resource-use efficiency and adaptive capacity.

Genomic Technologies recorded the strongest correlation with Climate-Resilient Crop Production ($r = 0.709$, $p < 0.01$), suggesting that

the development of climate-resilient crop varieties plays a critical role in enhancing agricultural sustainability.

The moderate correlations among the independent variables further indicate the complementary nature of these technological interventions.

Structural Equation Modeling and Hypothesis Testing

Table 5 presents the results of hypothesis testing.

Table 5: Hypothesis Testing Results

Hypotheses	Path	β	t-value	p-value	Decision
H1	BA \rightarrow CRCP	0.291	5.481	<0.001	Supported
H2	PA \rightarrow CRCP	0.327	6.104	<0.001	Supported
H3	GT \rightarrow CRCP	0.368	7.283	<0.001	Supported
H4	Integrated Technologies \rightarrow CRCP	0.581	10.426	<0.001	Supported

Structural Model Results

The structural model results indicate that all hypothesized relationships were statistically significant.

Hypothesis 1

The findings demonstrated that Biochar Application exerted a significant positive effect on Climate-Resilient Crop Production ($\beta = 0.291$, $t = 5.481$, $p < 0.001$). The result suggests that improvements in soil fertility, water retention, and nutrient availability substantially contribute to agricultural resilience and productivity under climatic stress conditions.

Hypothesis 2

Precision Agriculture significantly influenced Climate-Resilient Crop Production ($\beta = 0.327$, $t = 6.104$, $p < 0.001$). This finding indicates that technologies such as GIS, remote sensing, IoT sensors, and artificial intelligence improve decision-making processes, optimize resource

utilization, and enhance agricultural adaptability to environmental variability.

Hypothesis 3

Genomic Technologies exhibited the strongest individual influence on Climate-Resilient Crop Production ($\beta = 0.368$, $t = 7.283$, $p < 0.001$). The result suggests that the development of drought-tolerant, heat-resistant, and salinity-tolerant crop varieties substantially improves agricultural resilience and productivity.

Hypothesis 4

The integrated adoption of Biochar, Precision Agriculture, and Genomic Technologies demonstrated a highly significant positive effect on Climate-Resilient Crop Production ($\beta = 0.581$, $t = 10.426$, $p < 0.001$). The findings indicate that these technologies generate synergistic effects that are substantially greater than their individual contributions.

Coefficient of Determination

Table 6 presents the explanatory power of the structural model.

Table 6: Coefficient of Determination (R²)

Endogenous Variable	R ²	Adjusted R ²
Climate-Resilient Crop Production	0.671	0.667

The coefficient of determination ($R^2 = 0.671$) indicates that approximately 67.1% of the variation in Climate-Resilient Crop Production was explained by Biochar Application, Precision Agriculture, and Genomic Technologies. According to established SEM guidelines, this represents a substantial explanatory power.

The findings suggest that integrated climate-smart agricultural technologies constitute major determinants of climate-resilient agricultural production in Pakistan. The remaining 32.9% of unexplained variance may be attributable to other factors such as government support, institutional infrastructure, farmer awareness, financial resources, and policy interventions.

Overall, the empirical findings provide strong evidence that the integration of biochar, precision agriculture, and genomic technologies significantly enhances agricultural sustainability, resource-use efficiency, and climate resilience, thereby offering a viable pathway for ensuring food security and sustainable agricultural development in Pakistan.

Discussion

The present study investigated the integrated effects of biochar application, precision agriculture technologies, and genomic technologies on climate-resilient crop production in Pakistan. The empirical findings revealed that all three technological interventions exerted significant positive influences on climate-resilient crop production. Moreover, the integrated adoption of these technologies demonstrated a substantially stronger effect than their individual contributions, indicating the existence of synergistic relationships among biological, digital, and genomic innovations in enhancing agricultural resilience.

The findings demonstrated that biochar application significantly improved climate-

resilient crop production. This result is consistent with previous studies that identified biochar as an effective soil amendment capable of improving soil fertility, increasing water-holding capacity, enhancing nutrient retention, and promoting carbon sequestration (Khan et al., 2024; Rahim et al., 2026; Zhang et al., 2025). Earlier studies reported that biochar amendments improve crop productivity under drought and salinity conditions by improving soil physical and chemical properties and stimulating beneficial microbial activities. The present findings corroborate these conclusions and further demonstrate that biochar plays a significant role in strengthening agricultural resilience in climate-vulnerable regions such as Pakistan.

The positive and significant influence of precision agriculture technologies on climate-resilient crop production is also consistent with previous empirical evidence. Studies by Wolfert et al. (2017) and Javaid et al. (2023) concluded that technologies such as remote sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS), Internet of Things (IoT) sensors, and artificial intelligence significantly improve resource-use efficiency and facilitate evidence-based agricultural decision-making. Similarly, Shamshiri et al. (2018) reported that precision agriculture enhances crop monitoring capabilities and enables early responses to environmental stresses. The present study extends this body of knowledge by demonstrating that digital agricultural technologies significantly contribute to climate resilience within the context of Pakistan's agricultural systems.

The findings further revealed that genomic technologies exerted the strongest individual effect on climate-resilient crop production. This finding is consistent with previous studies emphasizing the importance of genomics, marker-assisted selection, genomic selection, and genome-editing

technologies in developing stress-tolerant crop varieties (Crossa et al., 2017; Bharat et al., 2023; Thingujam et al., 2025). Previous literature has highlighted the capacity of modern genomic technologies to accelerate crop breeding and develop cultivars capable of tolerating drought, heat stress, salinity, and emerging pests and diseases. The present findings support these arguments and indicate that genomic innovations constitute one of the most promising strategies for ensuring sustainable crop production under changing climatic conditions.

One of the most significant findings of this study is that the integrated adoption of biochar, precision agriculture, and genomic technologies produced the strongest influence on climate-resilient crop production. This finding provides empirical support for recent scholarly arguments advocating systems-based and multidisciplinary approaches to climate-smart agriculture (Das et al., 2024; Kabato et al., 2025). Existing studies have generally investigated these technologies independently, resulting in fragmented understanding and limited knowledge regarding their interactions and complementarities. The present study demonstrates that agricultural resilience can be significantly enhanced when soil management innovations, digital technologies, and advanced breeding strategies are implemented simultaneously rather than in isolation.

From a theoretical perspective, the findings strongly support the assumptions of the Climate-Smart Agriculture (CSA) Theory. The theory proposes that agricultural systems should simultaneously achieve increased productivity, improved climate adaptation, and environmental sustainability. The empirical findings demonstrate that biochar contributes to environmental sustainability and soil resilience, precision agriculture improves resource-use efficiency and adaptive management capabilities, and genomic technologies enhance crop resilience to climatic stresses. Their integration therefore directly contributes to all three pillars of climate-smart agriculture.

Furthermore, the findings extend the application of Climate-Smart Agriculture Theory by empirically demonstrating that technological

integration generates synergistic effects that substantially improve climate resilience and sustainable agricultural production. Consequently, the study advances the theoretical understanding of climate-smart agricultural systems by proposing an integrated framework that combines biological, digital, and genomic innovations within a single conceptual model.

Conclusion

Climate change poses unprecedented challenges to Pakistan's agricultural sector through increasing temperatures, irregular precipitation patterns, water scarcity, soil degradation, and the growing frequency of extreme climatic events. These challenges threaten agricultural productivity, environmental sustainability, and national food security.

The findings of this study indicate that biochar application, precision agriculture technologies, and genomic technologies individually and collectively contribute significantly to climate-resilient crop production in Pakistan. Biochar improves soil quality and resource retention, precision agriculture enhances resource-use efficiency through intelligent and site-specific management practices, and genomic technologies facilitate the development of stress-tolerant crop varieties capable of sustaining productivity under adverse environmental conditions.

The study further demonstrates that the integrated implementation of these technologies produces synergistic benefits that substantially strengthen agricultural resilience and sustainability. The proposed integrated framework therefore provides a practical and scientifically robust pathway toward achieving climate-smart agriculture, sustainable intensification, and food security in Pakistan.

Overall, the study concludes that the future sustainability of Pakistan's agricultural sector depends increasingly on the adoption of integrated technological innovations that simultaneously address soil degradation, resource constraints, and climate-induced production risks.

Implications

Theoretical Implications

The study contributes significantly to the emerging literature on climate-smart agriculture by extending the applicability of Climate-Smart Agriculture Theory within developing-country contexts. Unlike previous studies that primarily examined biochar, precision agriculture, and genomic technologies independently, this study develops and empirically validates an integrated and multidisciplinary framework for climate-resilient crop production.

The findings also contribute to the literature on sustainable agricultural intensification and agricultural resilience by demonstrating that technological complementarities generate stronger impacts than isolated interventions. Consequently, the study advances theoretical understanding regarding the interactions among biological, digital, and genomic innovations in climate-smart agricultural systems.

Managerial Implications

The findings provide important insights for agricultural managers, agribusiness organizations, extension agencies, and research institutions. Agricultural managers can utilize integrated technological approaches to optimize resource allocation, improve productivity, and reduce climate-related production risks.

Agribusiness organizations may employ digital farming technologies and biotechnology solutions to improve operational efficiency and sustainability. Agricultural extension departments can also utilize the findings to design effective training programs aimed at increasing farmers' awareness and technological adoption capabilities.

Practical Implications

The study provides practical guidance for farmers and agricultural practitioners regarding sustainable agricultural management practices. The findings suggest that biochar application can improve soil health and water-use efficiency, precision agriculture can facilitate intelligent farm management, and genomic technologies can provide improved crop varieties capable of tolerating climatic stresses.

The integrated framework proposed by this study may therefore assist agricultural stakeholders in improving productivity, minimizing environmental degradation, reducing production costs, and enhancing resilience against climate-induced agricultural uncertainties.

Policy Implications

The findings offer important policy insights for government agencies and policymakers responsible for agricultural development and climate adaptation planning. The study highlights the necessity of investing in agricultural research infrastructure, digital technologies, biotechnology programs, and sustainable soil management practices.

The findings also indicate the importance of formulating national policies that promote precision agriculture adoption, support biochar production initiatives, strengthen genomic research programs, and facilitate collaboration among universities, research institutions, and agricultural industries. Such policy interventions can significantly contribute to achieving food security and climate resilience in Pakistan.

Recommendations

Based on the findings of the study, the following recommendations are proposed:

1. Promote Large-Scale Biochar Adoption

Government agencies should establish incentive programs and technical support mechanisms to encourage the production and utilization of biochar from agricultural residues. Subsidized biochar initiatives may improve soil health and reduce environmental degradation.

2. Expand Precision Agriculture Infrastructure

Investment should be made in digital agricultural infrastructure, including remote sensing systems, GIS facilities, IoT-based monitoring systems, and artificial intelligence applications. Improving access to digital technologies can significantly enhance resource-use efficiency and climate adaptation capacity.

3. Strengthen Agricultural Biotechnology Programs

Research institutions and universities should intensify efforts to develop climate-resilient crop varieties through genomic selection, marker-assisted breeding, and genome-editing technologies. Increased investment in biotechnology research is essential for improving agricultural resilience.

4. Improve Farmer Training and Capacity Building

Agricultural extension departments should implement comprehensive training programs aimed at improving farmers' knowledge and technical competencies regarding biochar applications, precision agriculture technologies, and climate-smart farming practices.

5. Establish Integrated Climate-Smart Agricultural Centers

The government should establish multidisciplinary agricultural innovation centers that facilitate collaboration among soil scientists, agricultural engineers, plant breeders, and technology specialists for developing integrated climate-smart agricultural solutions.

6. Formulate Supportive Agricultural Policies

Policymakers should formulate comprehensive national strategies that encourage technological integration, facilitate technology transfer, improve financing mechanisms, and support sustainable agricultural intensification initiatives.

Limitations and Future Directions

Limitations of the Study

First, the study employed a cross-sectional research design, which restricted the examination of causal relationships and technological effects over time. Second, the study primarily relied on self-reported perceptions of respondents, which may be susceptible to response bias and subjective interpretations.

Third, the study was conducted within the context of Pakistan's agricultural sector, thereby limiting the generalizability of findings to other countries

possessing different environmental, technological, and institutional conditions.

Fourth, the study focused primarily on three technological interventions and did not incorporate other potentially influential variables such as financial constraints, institutional support mechanisms, farmers' behavioral intentions, and socioeconomic factors.

Future Research Directions

Future studies should employ longitudinal research designs to examine the long-term impacts of integrated technological interventions on agricultural resilience and productivity.

Researchers may also conduct comparative studies across different countries and agroecological regions to improve the generalizability of findings and identify context-specific determinants of climate-smart agricultural adoption.

Future investigations should incorporate additional variables, including government support, institutional quality, technological readiness, financial accessibility, and farmers' innovation capabilities as mediating or moderating variables.

Moreover, mixed-methods research combining quantitative and qualitative approaches may provide deeper insights into the implementation challenges, adoption barriers, and contextual dynamics associated with integrated climate-smart agricultural systems.

Finally, future studies should develop and empirically test advanced systems models that integrate biochar application, digital agriculture, artificial intelligence, biotechnology, and socio-institutional factors to establish comprehensive frameworks for sustainable and climate-resilient agricultural development.

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