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ECONOMIC MODELING OF CLIMATE-RESILIENT AGRICULTURE: STRATEGIES FOR SUSTAINABLE FOOD PRODUCTION AND INCOME STABILITY

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Abstract

Climate change increasingly threatens agricultural productivity, food security, and rural livelihoods through rising temperatures, irregular rainfall, prolonged droughts, flooding, soil degradation, and escalating production costs. This study develops an integrated economic modelling framework to evaluate the effectiveness of climate-resilient agricultural strategies in promoting sustainable food production, efficient resource utilization, and farm-income stability. A three-year panel dataset covering 480 farms across four agroecological zones was analysed, including 240 farms adopting climate-resilient practices and 240 conventionally managed farms. Data were obtained from structured household surveys, farm production records, meteorological observations, market-price databases, soil assessments, irrigation records, and satellite-derived vegetation indices. The evaluated strategies included drought-tolerant crop varieties, crop diversification, conservation tillage, precision irrigation, integrated soil-fertility management, agroforestry, and weather-indexed crop insurance. Descriptive statistics, fixed-effects panel regression, stochastic frontier analysis, cost--benefit analysis, and Monte Carlo simulation were employed to estimate productivity, profitability, technical efficiency, investment feasibility, and climate-risk exposure. Results showed that climate-resilient farms achieved an average crop yield of 5.84 t/ha, compared with 4.63 t/ha for conventional farms, representing a 26.1% improvement. Water-use efficiency increased by 29.4%, while fertilizer consumption and climate-related crop losses decreased by 17.8% and 24.6%, respectively. Average net farm income reached US$2,986/ha under climate-resilient management, compared with US$2,214/ha under conventional production, generating a 34.9% income advantage. Income variability declined by 21.7%, indicating greater financial stability under adverse climatic conditions. The integrated adaptation package produced a benefit--cost ratio of 1.89, a net present value of US$3,764/ha, an internal rate of return of 28.6%, and a payback period of 2.7 years. Regression findings revealed that irrigation efficiency, crop diversification, soil-health management, access to climate information, agricultural extension, and institutional credit significantly improved profitability and resilience. Scenario simulations indicated that integrated adaptation could restrict projected climate-induced yield losses to 8.6%, compared with 23.9% under conventional farming. The study concludes that coordinated investments in climate-resilient technologies, affordable finance, extension services, insurance, and climate-information systems can simultaneously improve food production, stabilize farm income, and advance sustainable agricultural development.

Keywords: Climate-Resilient Agriculture; Economic Modelling; Sustainable Food Production; Farm-Income Stability; Climate Adaptation; Resource-Use Efficiency; Food Security; Agricultural Risk Management

1. Introduction

Climate change has become one of the most significant threats to agricultural productivity, food security, and rural economic development. Rising temperatures, irregular rainfall, prolonged droughts, severe flooding, soil degradation, and increasingly frequent extreme weather events are disrupting conventional farming systems and reducing the reliability of agricultural production. These challenges are particularly serious in regions where agriculture depends heavily on rainfall, farmers have limited financial resources, and access to advanced agricultural technologies remains inadequate. At the same time, rising costs of irrigation, fertilizer, energy, labor, and crop protection are placing additional pressure on farm profitability. The agricultural sector must therefore increase food production while protecting farmers' incomes under increasingly uncertain climatic and economic conditions (Saha, 2024). The economic consequences of climate change extend considerably beyond reductions in crop yield. Climate-related shocks can increase production costs, reduce the efficiency of agricultural inputs, damage infrastructure, disrupt supply chains, and create substantial fluctuations in farm revenue. Repeated crop failures may force farmers to sell productive assets, reduce investment, accumulate debt, or shift away from high-value crops. These responses can weaken long-term agricultural productivity and increase rural households' vulnerability to poverty and food insecurity. Therefore, the effectiveness of climate adaptation cannot be assessed exclusively through agronomic indicators. It must also be examined in terms of profitability, income stability, technical efficiency, investment feasibility, and the capacity of farming systems to withstand and recover from climatic shocks.

Climate-resilient agriculture provides an integrated approach to managing these interconnected challenges. It encompasses technologies, practices, and institutional mechanisms intended to improve productivity, conserve natural resources, and reduce exposure to climatic risks. Drought-tolerant crop varieties can maintain production under water-stressed conditions, while crop diversification reduces dependence on a single commodity and distributes risk across several sources of income (Perez et al., 2021). Conservation tillage improves soil structure, limits erosion, and supports moisture retention. Precision irrigation increases water-use efficiency by delivering water according to crop requirements, whereas integrated soil-fertility management improves nutrient availability while reducing excessive dependence on chemical fertilizers. Agroforestry can enhance soil quality, diversify farm revenue, and protect crops against climatic extremes. Weather-indexed crop insurance can also provide financial protection when adverse weather conditions cause significant production losses.

Although individual climate-resilient practices may generate important benefits, their performance can vary considerably across farming systems and agroecological conditions. A strategy that performs successfully in a drought-prone region may be less effective in an area characterized by flooding, salinity, or severe land degradation. Adoption outcomes are also influenced by farm size, farmer education, household resources, market access, land-tenure arrangements, institutional credit, extension services, and access to reliable climate information. High initial investment costs and uncertainty regarding future benefits may further discourage adoption, particularly among smallholder farmers. A comprehensive economic assessment is therefore necessary to determine whether climate-resilient strategies are productive, affordable, financially viable, and effective in reducing climate-related risk. Previous research has provided valuable evidence regarding climate-smart technologies, sustainable land management, irrigation efficiency, crop diversification, and agricultural adaptation (Ahmad et al., 2025). However, many studies focus on individual practices or short-term changes in crop yield. Comparatively limited attention has been paid to the combined effects of adaptation strategies on productivity, technical efficiency, resource utilization, profitability, and income variability over multiple production years. Moreover, conventional statistical assessments frequently rely on average historical values and may not adequately represent uncertainty in rainfall, temperature, crop prices, input costs, and production losses. This limitation is important because both farmers and policymakers must make investment decisions under changing climatic and market conditions.

Economic modeling can help address these limitations by integrating farm-level production information with climatic, environmental, socioeconomic, and market data. Panel-data models can control for unobserved farm-specific characteristics and estimate the effects of adaptation practices over time. Stochastic frontier analysis can determine whether climate-resilient farms utilize available resources more efficiently than conventionally managed farms. Cost-benefit analysis can evaluate financial feasibility through indicators such as net present value, benefit-cost ratio, internal rate of return, and payback period. Monte Carlo simulation can further incorporate uncertainty by estimating the probability and distribution of potential outcomes under alternative climatic and economic scenarios (Meena et al., 2026). The combination of these approaches provides a robust basis for examining both the expected benefits and financial risks associated with climate adaptation. Against this background, the present study develops an integrated economic modeling framework to assess the effectiveness of climate-resilient agriculture in promoting sustainable food production, efficient resource utilization, and farm-income stability. The analysis is based on a three-year panel dataset covering 480 farms across four agroecological zones, including 240 farms adopting climate-resilient practices and 240 conventionally managed farms.

Data is obtained from structured household surveys, farm production records, meteorological observations, market-price databases, soil assessments, irrigation records, and satellite-derived vegetation indices. The evaluated adaptation strategies include drought-tolerant crop varieties, crop diversification, conservation tillage, precision irrigation, integrated soil-fertility management, agroforestry, and weather-indexed crop insurance. The study examines the effects of these strategies on crop yield, water-use efficiency, fertilizer consumption, technical efficiency, climate-related crop losses, profitability, and net farm income (Gorripati et al., 2023). It also determines whether climate-resilient management can reduce income variability and remain financially attractive after accounting for establishment costs, operating expenditures, investment duration, and uncertainty. Particular consideration is given to enabling factors such as agricultural extension, institutional credit, climate-information access, irrigation infrastructure, and crop insurance because these factors can strongly influence adoption decisions and long-term economic outcomes.

The principal contributions of this study are as follows:

- It develops an integrated economic modeling framework that connects climate adaptation with agricultural productivity, resource-use efficiency, profitability, and income stability.
- It uses a three-year panel dataset of 480 farms to provide a longitudinal comparison between climate-resilient and conventionally managed agricultural systems.
- It evaluates a coordinated package of seven climate-resilient strategies rather than examining individual agricultural practices in isolation.
- It combines fixed-effects panel regression, stochastic frontier analysis, cost-benefit analysis, and Monte Carlo simulation to generate multidimensional evidence regarding performance, efficiency, financial feasibility, and risk.
- It integrates household, production, climatic, market, soil, irrigation, and satellite-derived information to improve the reliability and comprehensiveness of the economic assessment.

Overall, this study positions climate-resilient agriculture as both an environmental adaptation strategy and an economically viable pathway for sustainable rural development. Its integrated framework provides practical evidence for farmers, policymakers, financial institutions, insurance providers, and agricultural-development organizations seeking to improve food production while reducing vulnerability to climatic and economic shocks. The findings can support the development of agricultural policies that promote efficient resource use, stable rural incomes, and long-term food-system resilience under a changing climate.

2. Drought-Tolerant Varieties and Climate-Responsive Crop Selection

Drought-tolerant and heat-resistant crop varieties represent an important component of climate-resilient agriculture because they enable farmers to maintain production under limited soil moisture, irregular rainfall, and elevated temperatures. These varieties are developed or selected to perform more reliably under environmental stress through characteristics such as deeper root systems, shorter growth cycles, improved water-use efficiency, reduced transpiration losses, and greater tolerance to heat during flowering and grain formation. Compared with conventional varieties, climate-responsive crops can reduce the probability of complete crop failure and stabilize agricultural output during unfavorable seasons. The importance of drought-tolerant varieties has increased as rainfall patterns have become less predictable and irrigation resources more constrained (Oyadeyi & Oyadeyi, 2025). Conventional crop varieties are frequently selected according to historical climatic conditions, which may no longer represent current or future production environments. Climate-responsive selection instead considers expected rainfall, temperature, soil-moisture availability, planting windows, crop-growth duration, and the probability of extreme weather events. This approach enables farmers to select crops and varieties that are more closely aligned with changing agroecological conditions.

The economic value of drought-tolerant crops is associated not only with potentially higher yields under water stress but also with lower production variability. Greater yield stability can help farmers maintain household consumption, meet market commitments, purchase inputs for the following season, and repay agricultural loans (Ahmad et al., 2026). Drought-tolerant varieties may also reduce the need for emergency irrigation, repeated sowing, and other corrective interventions. Consequently, their benefits include avoided production losses and cost savings in addition to direct improvements in crop yield. However, the financial performance of these varieties is influenced by several conditions. Improved seeds may have higher purchase prices than traditional seeds, and some varieties may require specialized fertilizer, irrigation, or planting practices. Their adoption may also be constrained by limited availability, inadequate extension support, uncertain market acceptance, and farmers' preference for familiar varieties. Therefore, performance should be evaluated using multiple agronomic and economic indicators rather than relying exclusively on average crop yield. The major characteristics, indicative values, benefits, and constraints associated with drought-tolerant crop varieties are presented in Table 1.

Table 1

Characteristics, Indicative Values, and Expected Benefits of Drought-Tolerant Crop Varieties

Characteristic	Agronomic function	Indicative evaluation value
Deep and extensive root system	Improves access to moisture stored in deeper soil layers	Root depth: 80--150 cm
Shorter crop duration	Allows crops to mature before severe late-season drought	Maturity: 90--120 days
Improved water-use efficiency	Produces more marketable output from available water	Improvement: 15--30%
Heat-stress tolerance	Maintains flowering, pollination, and grain formation under elevated temperatures	Tolerance range: 35--40°C
Improved yield stability	Reduces variation in production between normal and drought years	Yield variability reduction: 10--25%
Reduced irrigation requirement	Maintains growth with lower water application	Water saving: 15--25%
Pest and disease resistance	Limits climate-related pest and disease damage	Crop-loss reduction: 8--20%

Climate-responsive crop selection extends beyond the distribution of improved seeds. It involves matching the crop type, genetic variety, planting date, maturity period, irrigation demand, and expected market value with local climatic and socioeconomic conditions. Historical meteorological records can be combined with seasonal forecasts to estimate expected rainfall and temperature patterns. Soil assessments can determine water-holding capacity and nutrient availability, while irrigation records indicate whether supplemental water can be supplied during critical growth stages (Zong et al., 2022). Market-price information is also necessary to ensure that the selected crop has adequate demand and can generate an acceptable financial return. The integrated crop-selection process is illustrated in Figure 1. The framework begins with the assessment of climatic conditions, soil and water resources, farm capacity, and market opportunities. This information supports the identification of suitable drought- and heat-tolerant varieties. Field-level management practices are then aligned with the selected variety to improve its performance. The expected

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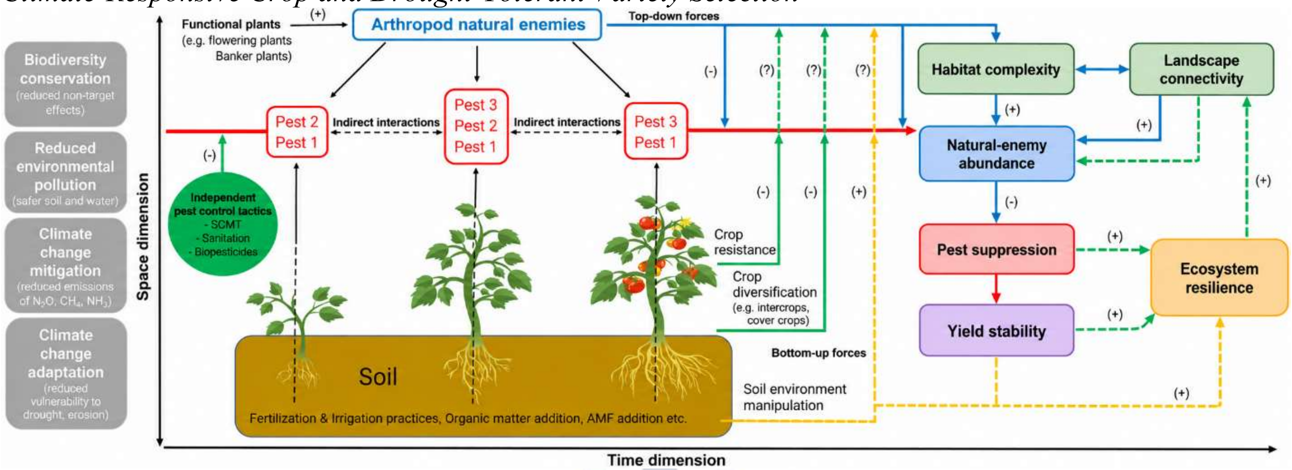
outcomes include greater yield stability, more efficient use of water, lower climate-related losses, and improved farm-income stability.

Figure 1

Climate-Responsive Crop and Drought-Tolerant Variety Selection



Rainfall and temperature forecasts identify likely climatic pressures, while soil and irrigation assessments establish whether the farm can support the water and nutrient requirements of a particular crop. Farm-level resources including available land, labor, machinery, financial capacity, and technical knowledge determine whether the variety can be managed effectively. Market assessment ensures that production decisions are consistent with consumer demand and expected output prices. After selecting a suitable variety, farmers must adjust planting dates, seed rates, irrigation schedules, fertilizer applications, and pest-management practices. Drought tolerance alone cannot compensate for poor crop management, degraded soil, delayed planting, or inefficient irrigation (Meena et al., 2026). The greatest benefits are therefore expected when improved genetics are combined with conservation tillage, soil-moisture protection, precision irrigation, balanced fertilizer application, and timely climate information. Despite their potential, several barriers restrict the large-scale adoption of climate-responsive crop varieties.

Certified seed may be expensive or unavailable in remote agricultural markets. Farmers may also lack information about yield performance under local conditions or may be reluctant to replace traditional varieties valued for their taste, storage quality, cultural importance, or established market demand. Limited access to credit can further prevent resource-constrained farmers from purchasing improved seeds and complementary inputs. Extension services and participatory field demonstrations can reduce these barriers by allowing farmers to compare improved and conventional varieties under actual production conditions. Participatory selection can also ensure that varietal recommendations incorporate farmers' preferences regarding maturity, productivity, quality, marketability, and household consumption (Srivastav et al., 2021). Moreover, public and private investment in seed production, certification, distribution, and local breeding programs can improve the affordability and availability of climate-responsive varieties. Drought-tolerant varieties can strengthen agricultural resilience by reducing climate-related production losses, improving water-use efficiency, and stabilizing farm revenue. Nevertheless, their performance depends on appropriate agroecological matching, effective crop management, reliable climate information, seed accessibility, and market acceptance. Drought-tolerant crops should therefore be implemented as part of an integrated adaptation package that combines technological innovation with soil management, efficient irrigation, financial support, extension services, and climate-risk management.

3. Conservation Tillage and the Economic Value of Healthy Soil

Soil health is a fundamental determinant of agricultural productivity, resource-use efficiency, and long-term farm profitability. However, intensive ploughing, continuous monocropping, residue removal,

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excessive chemical inputs, and poor land management can reduce soil organic matter, weaken soil structure, accelerate erosion, and limit water-retention capacity. Climate change further intensifies these problems through rising temperatures, prolonged droughts, intense rainfall, and flooding. As soil quality deteriorates, farmers may require greater quantities of fertilizer, irrigation water, fuel, and labor to maintain production, resulting in higher costs and declining economic returns. Conservation tillage provides an important climate-resilient alternative to intensive soil cultivation. It reduces mechanical disturbance and maintains a protective layer of crop residue on the soil surface. Its principal forms include minimum tillage, reduced tillage, strip tillage, ridge tillage, and zero or no-tillage.

These practices support soil aggregation, conserve moisture, reduce erosion, limit surface runoff, and improve the accumulation of organic matter (Fagbemi et al., 2023). Retaining crop residues also protects the soil from direct sunlight and reduces moisture loss during periods of elevated temperature. Healthy soil should be considered a productive economic asset rather than only an environmental resource. Improvements in soil organic matter, nutrient retention, microbial activity, and water-holding capacity can enhance crop performance over several production seasons. These improvements may reduce fertilizer and irrigation requirements while increasing the stability of yields under variable climatic conditions. Conservation tillage can also reduce the number of machinery operations required for land preparation, resulting in lower fuel consumption, labor demand, equipment depreciation, and operating costs. Nevertheless, the economic benefits of conservation tillage may not be immediate. Farmers can face initial expenses related to specialized machinery, residue management, herbicide application, and technical training. Crop yields may also fluctuate during the transition period as soil conditions and farm-management practices adjust to the new system (Ghimire et al., 2025). Therefore, conservation tillage should be assessed over multiple production years rather than evaluated through the results of a single season. The principal practices, indicative values, economic benefits, and implementation challenges are summarized in Table 2.

Table 2

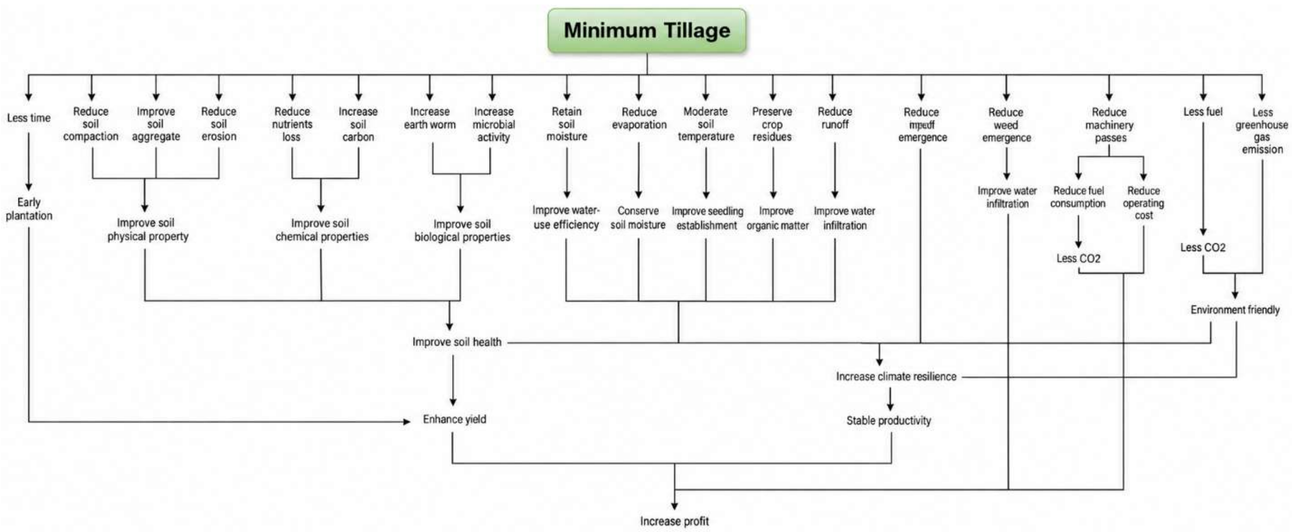
Conservation-Tillage Practices, Indicative Values, and Expected Economic Benefits

Conservation practice	Indicative evaluation value	Expected economic benefit
Minimum tillage	Tillage operations reduced by 30-50%	Lowers fuel, labor, and machinery costs
Zero or no-tillage	Soil disturbance below 10%	Produces substantial savings in land-preparation expenses
Crop-residue retention	Surface coverage of 30-70%	Reduces irrigation demand and protects future productivity
Strip tillage	Cultivated area reduced by 50-70%	Decreases energy use while maintaining suitable seedbeds
Contour tillage	Runoff reduction of 15-30%	Reduces soil and nutrient losses on sloping land
Cover cropping	Soil cover maintained for 2-4 additional months	Reduces erosion and may lower fertilizer expenditure
Controlled machinery traffic	Compacted area reduced by 20--40%	Improves root development and machinery efficiency
Moisture conservation	Soil-moisture retention increased by 10-25%	Lowers irrigation costs and protects yield during drought

Conservation tillage can generate both direct and indirect economic benefits. Direct benefits arise from reductions in fuel use, machinery operations, labor requirements, irrigation, and certain input costs. Indirect benefits include improved soil fertility, reduced erosion, greater moisture availability, more stable production, and protection of land value. These long-term benefits are especially important under climate change because healthy soils can absorb rainfall more effectively during intense storms and retain moisture for longer periods during drought (Rao et al., 2019). The relationship between conservation tillage, soil health, farm productivity, and economic performance is illustrated in Figure 2. Conservation practices initially influence the physical, chemical, and biological properties of soil. Improved soil conditions then support more efficient use of water and nutrients, reduce production losses, and strengthen crop growth. Over time, these changes can decrease production costs, stabilize crop yields, and improve farm profitability.

Figure 2

Economic Pathway Connecting Conservation Tillage, Soil Health, and Farm Profitability



Conservation tillage can also influence technical efficiency by enabling farms to produce more output with fewer machinery, fuel, labor, and water inputs. Reduced machinery passes can shorten the land-preparation period and allow farmers to plant crops at the most suitable time. Timely sowing is particularly important in areas with short or unpredictable rainfall seasons. In addition, reduced fuel consumption protects farmers from fluctuations in energy prices and decreases the carbon intensity of agricultural production (Ahmad et al., 2026). Despite these advantages, adoption remains constrained by economic and operational challenges. Specialized seed drills and residue-management machinery can require substantial initial investment. Small farms may not be able to purchase this equipment independently, while rental services may be unavailable or expensive. Crop residues also have competing uses such as livestock feed, fuel, and construction material, limiting the amount that can remain on the field. During the early transition period, farmers may experience increased weed pressure or uncertainty regarding fertilizer and pest-management requirements. Institutional support is therefore necessary to improve adoption. Equipment-sharing programs, machinery rental centers, targeted credit, and investment subsidies can reduce initial financial barriers. Extension services and field demonstrations can help farmers select tillage systems appropriate for their soil, crops, and climatic conditions. Soil testing and continuous monitoring can further provide evidence of changes in organic matter, nutrient availability, moisture retention, and compaction. Such information enables farmers to adjust management practices and recognize benefits that may not be visible during the first production season. From an economic perspective, conservation tillage should be evaluated by considering both annual cash flows and long-term changes in natural capital (Jena et al., 2023).

Immediate indicators may include fuel use, labor requirements, machinery expenses, irrigation costs, and crop revenue. Long-term assessment should incorporate changes in soil fertility, erosion, land value, yield stability, and the farm's ability to withstand climatic shocks. Cost-benefit analysis over multiple years can therefore provide a more accurate estimate of the practice's financial feasibility than a single-season comparison. Conservation tillage can improve the economic and environmental sustainability of agriculture by protecting soil resources, reducing production costs, increasing water-use efficiency, and stabilizing crop yield. Its success, however, depends on appropriate equipment, residue availability, farmer knowledge, soil conditions, and continued institutional support. When combined with crop diversification, drought-tolerant varieties, precision irrigation, and integrated soil-fertility management, conservation tillage can play a central role in developing productive, profitable, and climate-resilient farming systems.

4. Methodology

This study adopted a quantitative longitudinal research design to evaluate the economic, productive, and risk-reduction effects of climate-resilient agriculture. The methodological framework integrated farm-level socioeconomic characteristics, agricultural inputs, crop-production outcomes, climatic conditions, soil properties, irrigation use, market prices, and satellite-derived vegetation information. Data were collected over three consecutive agricultural years, allowing changes in farm performance to be examined across time and under varying climatic conditions. The principal outcomes included crop yield, water-use efficiency, fertilizer consumption, technical efficiency, climate-related crop losses, production costs, net farm income, and income variability (Durgude et al., 2026). A comparative approach was employed to assess differences between climate-resilient and conventionally managed farms. Climate-resilient farms were identified based on the continuous adoption of one or more recognized adaptation strategies, including drought-tolerant crop varieties, crop diversification, conservation tillage, precision irrigation, integrated soil-fertility management, agroforestry, and weather-indexed crop insurance. Conventionally managed farms served as the comparison group and primarily relied on established production practices without systematic integration of climate-adaptation measures.

The use of balanced groups and repeated farm-level observations supported a reliable evaluation of differences in productivity, resource efficiency, profitability, and resilience (Sridhar et al., 2025). The analytical strategy combined descriptive statistics, fixed-effects panel regression, stochastic frontier analysis, discounted cost--benefit analysis, and Monte Carlo simulation. Descriptive analysis summarized the demographic, agricultural, climatic, and financial characteristics of the sampled farms. Fixed-effects regression estimated the influence of adaptation practices and institutional factors on productivity and profitability, while stochastic frontier analysis measured technical efficiency. Cost--benefit indicators evaluated the financial feasibility of climate-resilient investments, and Monte Carlo simulation examined the sensitivity of economic outcomes to uncertainty in rainfall, temperature, crop prices, input costs, and yield losses. This integrated approach enabled the study to assess both the average economic benefits and the risk-reduction capacity of climate-resilient agriculture.

4.1 Multi-Zone Farm Sampling and Comparative Study Design

A multi-zone comparative research design was employed to evaluate the productive, economic, and climate-resilience performance of different agricultural management systems. The study covered four agroecological zones characterized by variations in rainfall, temperature, soil conditions, irrigation availability, cropping patterns, and exposure to climatic hazards. Including environmentally diverse zones enabled the study to examine whether the benefits of climate-resilient agriculture remained consistent under different farming conditions. A multistage stratified sampling technique was used to select participating farms. During the first stage, four agroecological zones were identified using meteorological information, soil characteristics, irrigation conditions, land-use patterns, and dominant production systems. Representative farming communities were subsequently selected within each zone (Islam & Fraser, 2026). Farms were then stratified according to management system, climate-resilient practice adoption, farm size, crop category, and irrigation access. Eligible farms were randomly selected from the resulting sampling lists to reduce selection bias. The final sample consisted of 480 farms, including 240 farms applying climate-resilient practices and 240 conventionally managed farms. As summarized in Table 3, 120 farms were selected from each agroecological zone, comprising 60 climate-resilient farms and 60 conventional farms. This balanced allocation ensured equal representation and supported direct comparisons between the two management systems across different environmental conditions.

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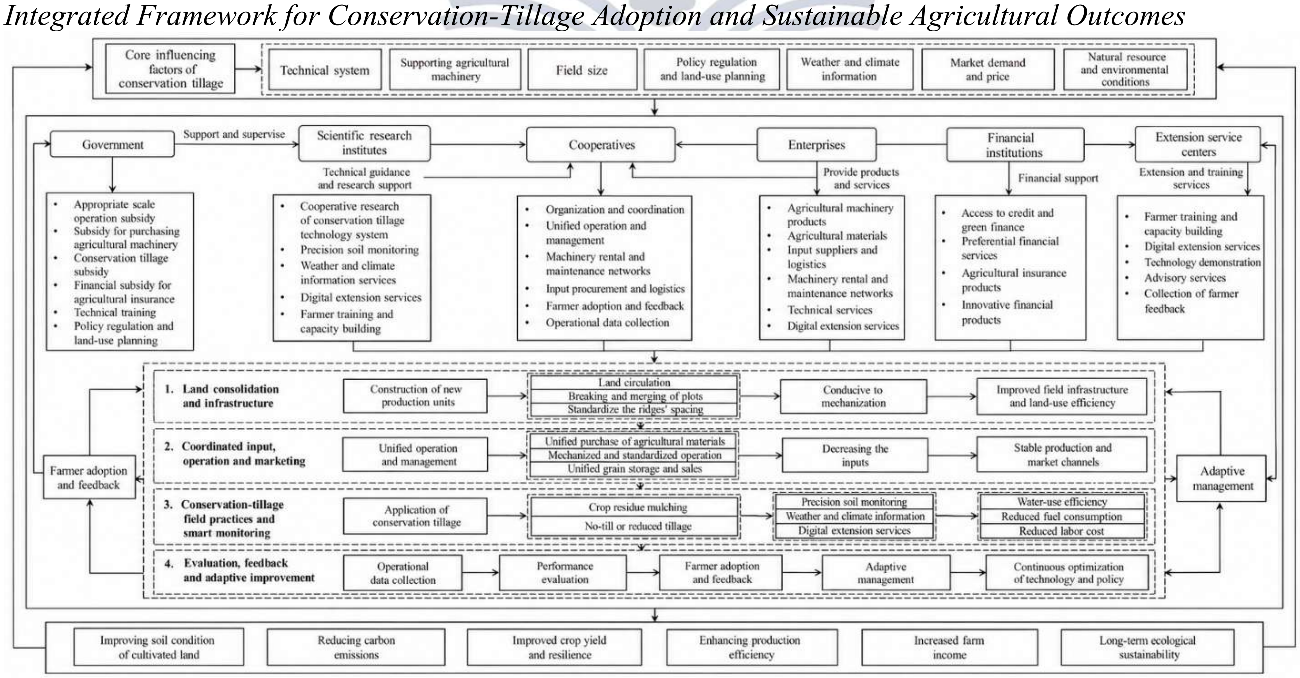
Table 3
Distribution and Comparative Characteristics of Sampled Farms Across Agroecological Zones

Agroecological zone	Climate-resilient farms	Conventional farms	Total farms	Share of total sample
Zone I	60	60	120	25.0%
Zone II	60	60	120	25.0%
Zone III	60	60	120	25.0%
Zone IV	60	60	120	25.0%
Total	**240**	**240**	**480**	**100.0%**

Climate-resilient farms were identified based on the sustained adoption of one or more recognized adaptation strategies during the study period. These strategies included drought-tolerant crop varieties, crop diversification, conservation tillage, precision irrigation, integrated soil-fertility management, agroforestry, and weather-indexed crop insurance. Information was collected on the type, number, duration, and intensity of the practices adopted. Farms applying several complementary measures were classified as integrated adopters, whereas farms implementing fewer measures were categorized according to their level of adoption (Biswal et al., 2025). Conventionally managed farms were selected from the same or closely comparable farming communities. These farms mainly relied on traditional crop varieties, conventional tillage, standard irrigation methods, routine fertilizer application, and limited formal climate-risk management. Selecting both groups from similar locations reduced differences in rainfall exposure, soil properties, infrastructure, transportation costs, and market access. This improved the likelihood that observed performance differences were associated with farm-management strategies rather than geographical separation. The farm-selection and comparative classification process is presented in Figure 3. The procedure began with the identification of the four agroecological zones, followed by the selection of representative communities and the screening of eligible farms. The farms were subsequently divided into climate-resilient and conventional groups, producing a balanced three-year panel dataset.

Figure 3
Integrated Framework for Conservation-Tillage Adoption and Sustainable Agricultural Outcomes



Farms with incomplete records, substantial changes in cultivated land, discontinuation of agricultural activity, or missing observations across survey rounds were excluded from the final panel. To strengthen group comparability, farms were assessed according to cultivated area, major crop category, household labor availability, farming experience, irrigation access, market conditions, and access to agricultural services. The same farms were followed throughout the three-year period, generating repeated observations for each production unit. This longitudinal structure allowed the analysis to distinguish yearly changes caused by weather and markets from persistent farm-level characteristics (Singh et al., 2020). The comparative assessment included crop yield, cultivated area, water consumption, fertilizer use, production costs, gross revenue, net income, technical efficiency, and climate-related crop losses. Year-to-year changes in yield and net farm income were also examined to determine whether climate-resilient farms experienced lower variability during adverse production seasons.

This distinction was important because an adaptation strategy may generate limited benefits under normal conditions but provide substantial protection during droughts, floods, heatwaves, or irregular rainfall. Participation in the study was voluntary, and farmers received information about the research objectives, data requirements, confidentiality procedures, and intended use of the findings. Informed consent was obtained before surveys, and field assessments were conducted. Each farm was assigned a unique identification code, enabling observations to be connected across the three-year period without including personal identifiers in the analytical dataset (Kumar et al., 2026). The balanced multi-zone sampling design provided a reliable foundation for evaluating climate-resilient agriculture across diverse environmental and production conditions. Equal representation of climate-resilient and conventional farms supported meaningful group comparisons, while the longitudinal structure enabled the assessment of both average performance and stability over time. The design also supported zone-specific analysis, fixed-effects estimation, and evaluation of how local climate and resource conditions influenced the economic effectiveness of adaptation strategies.

4.2 Agricultural Productivity and Resource-Efficiency Measurement

Agricultural productivity and resource-use efficiency were measured to determine whether climate-resilient practices enabled farms to produce higher and more stable output with fewer natural and purchased inputs. The assessment considered crop yield, total production, water-use efficiency, fertilizer-use efficiency, labor productivity, energy consumption, soil-health performance, and climate-related crop losses. These indicators captured both the immediate production effects and the longer-term sustainability of farm management. Farm-level information was collected for three consecutive years to account for seasonal changes in rainfall, temperature, input use, crop performance, and climatic stress (Farooq et al., 2026). Production and input indicators were standardized on a per-hectare basis to ensure valid comparisons among farms of different sizes. Where farms cultivated multiple crops, crop-specific values were initially calculated separately and subsequently aggregated using cultivated area and farm-gate value. Crop yield was calculated as the quantity of harvested output produced per hectare of cultivated land. Marketable output excluded produce damaged beyond acceptable consumption or market-quality standards. Harvest information was verified using farm records, sales receipts, storage records, and structured farmer interviews. Where direct field measurements were available, they were used to verify the accuracy of self-reported production quantities.

Water-use efficiency was evaluated by comparing crop output with the total volume of irrigation water applied. Irrigation records included the number and duration of irrigation events, estimated discharge rates, water-source types, and seasonal water use. Rainfall information was considered when interpreting irrigation demand because farms receiving more effective rainfall might require less supplementary water. Higher output per unit of applied water indicated stronger water-use efficiency, whereas excessive irrigation without a corresponding yield improvement indicated resource inefficiency. Fertilizer-use efficiency was measured by relating agricultural output to the quantity of nutrients applied. Fertilizer inputs were recorded according to type, application rate, frequency, and cultivated area (Huyer et al., 2021). The analysis considered whether climate-resilient farms maintained or increased yield while reducing fertilizer consumption. This distinction was essential because lower fertilizer use alone does not represent improved efficiency when accompanied by a substantial reduction in crop output. Labor and energy productivity were also included because climate-resilient practices may alter the operational requirements of farming. Labor input was measured through

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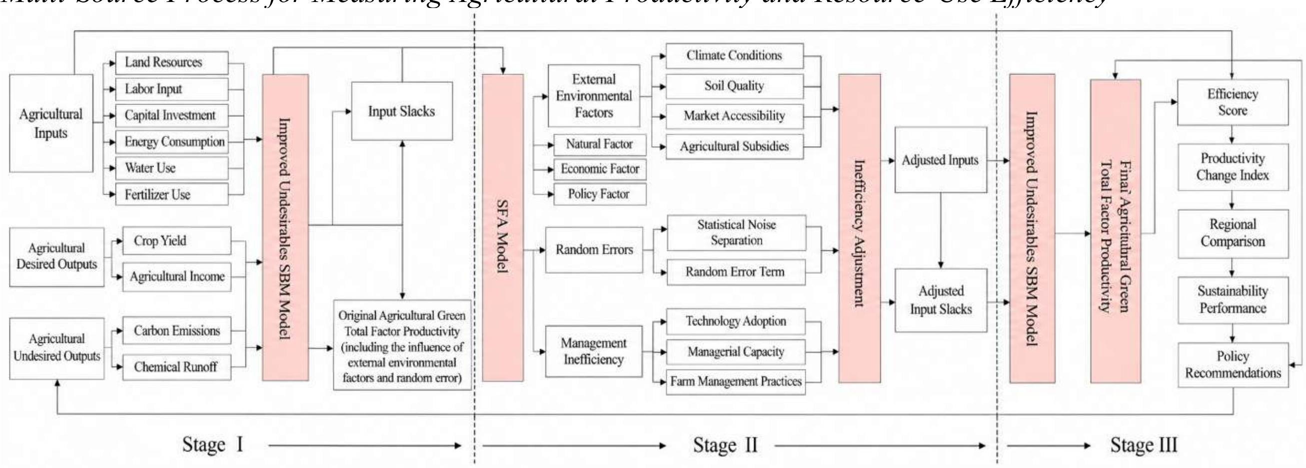
family and hired labor days devoted to land preparation, planting, irrigation, fertilizer application, pest management, harvesting, and post-harvest handling. Energy consumption included fuel used by tractors and irrigation pumps, electricity use, and other machinery-related energy requirements.

These indicators enabled the study to determine whether conservation tillage, precision irrigation, and improved management reduced production inputs while maintaining output. Soil assessments provided supporting measures of long-term resource efficiency (Goswami et al., 2023). Soil organic matter, moisture content, nutrient availability, structure, and erosion exposure were examined to assess whether conservation tillage, agroforestry, and integrated soil-fertility management improved productive capacity. Satellite-derived vegetation indices were used to complement farm and soil observations by monitoring crop vigor, vegetation stress, and spatial differences in crop condition. The integration of farm records, field assessments, and satellite information reduced dependence on a single data source. The measurement and verification process is presented in Figure 4. Data from farm records, irrigation systems, soil assessments, meteorological stations, and satellite observations were standardized and combined to generate productivity, efficiency, and climate-resilience indicators.

Figure 4

Multi-Source Process for Measuring Agricultural Productivity and Resource-Use Efficiency



Measurements from different sources were processed before comparisons were performed. Monetary variables were adjusted to a common price basis to limit the influence of inflation and annual market-price fluctuations. Physical inputs and outputs were converted into consistent units, while extreme or inconsistent observations were cross-checked against original farm records. Missing observations were examined carefully and treated according to their cause and extent rather than replaced automatically. Climate-related crop losses were estimated by comparing expected production under normal conditions with the output achieved following droughts, floods, heat stress, or irregular rainfall. Expected output was informed by historical farm performance, crop-specific benchmarks, and production levels recorded in less-affected seasons. Losses were expressed as a percentage of expected output, enabling comparison across crops and farm sizes. This indicator captured the protective effect of adaptation practices against adverse climatic events. Yield and income stability were assessed using variation across the three study years (Dinesha et al., 2023).

Lower year-to-year variability indicated that a farm maintained more consistent performance despite changes in climate and market conditions. This stability measure complemented average yield because farms with similar mean production levels could experience substantially different levels of annual risk. The measurement framework linked agricultural output with land, water, fertilizer, labor, energy, and soil resources used to generate it. The combined indicators provided a multidimensional assessment of whether climate-resilient agriculture improved productivity while reducing pressure on limited resources. This framework also supplied the variables required for the subsequent panel-regression, stochastic-frontier, cost-benefit, and climate-risk analyses.

4.3 Stochastic Frontier Analysis of Farm-Level Efficiency

Stochastic frontier analysis (SFA) was employed to measure farm-level technical efficiency and determine whether climate-resilient farms produced output more efficiently than conventionally managed farms. Technical efficiency refers to a farm's ability to obtain the maximum feasible output from a given combination of land, labor, water, fertilizer, seed, machinery, and energy inputs. The method was appropriate because agricultural output is affected by both managerial performance and uncontrollable factors such as rainfall variability, temperature shocks, pests, flooding, and measurement errors. Unlike conventional regression, SFA separates deviations from potential output into two components: random statistical noise and farm-level inefficiency. Random noise represents temporary conditions beyond the farmer's direct control, while the inefficiency component captures output losses associated with weak input allocation, poor management, limited technical knowledge, or institutional constraints (Ozoji et al., 2025). This distinction prevented weather-related shocks from being incorrectly classified as farmer inefficiency. Crop output was used as the dependent production variable, while cultivated land, labor, irrigation water, fertilizer, seed expenditure, machinery use, and energy consumption were included as production inputs. Climate variables particularly rainfall, temperature, drought exposure, and flooding frequency were incorporated to account for environmental differences across farms and years. The main production and inefficiency variables included in the SFA model are described in Table 4.

Table 4

Variables Used in the Stochastic Frontier Efficiency Analysis

Variable category	Expected influence	Analytical purpose
Production output	Dependent variable	Represents realized farm production
Land input	Positive	Captures the scale of agricultural production
Labor input	Positive	Measures human effort used in production
Irrigation input	Positive to optimal level	Evaluates the productivity of water use
Fertilizer input	Positive to optimal level	Captures the contribution of soil nutrients
Seed input	Positive	Represents crop-establishment intensity
Machinery input	Positive	Measures mechanized production support
Energy input	Positive to optimal level	Captures energy dependence and operational intensity
Climate condition	Positive or nonlinear	Controls for available climatic moisture
Climate stress	Negative	Controls for production shocks
Adaptation status	Positive	Measures the contribution of adaptation
Inefficiency factor	Reduces inefficiency	Reflects knowledge and decision-making capacity

The production-frontier component estimated the maximum potential output attainable from the observed combination of agricultural inputs. A flexible production specification was adopted to capture variations in input productivity and possible interactions among land, labor, water, fertilizer, and machinery. Farm and year observations were retained across the three-year panel, enabling the model to reflect temporal changes in resource utilization and climatic conditions. Farm-specific technical-efficiency scores were generated on a scale ranging from zero to one. A value closer to one indicated that a farm operated near the estimated production frontier, while a lower score represented a larger gap between observed and potential output. For example, a score of 0.80 would indicate that the farm achieved approximately 80% of the output considered feasible under its observed input and production conditions (Mereu et al., 2018).

The remaining gap would represent the potential for improvement through better management and resource allocation rather than additional input expansion. The inefficiency model examined whether socioeconomic and institutional factors explained differences in farm performance. Education and farming experience were included because they can improve the ability to understand new technologies and allocate resources appropriately. Extension contacts and access to climate information were expected to support timely

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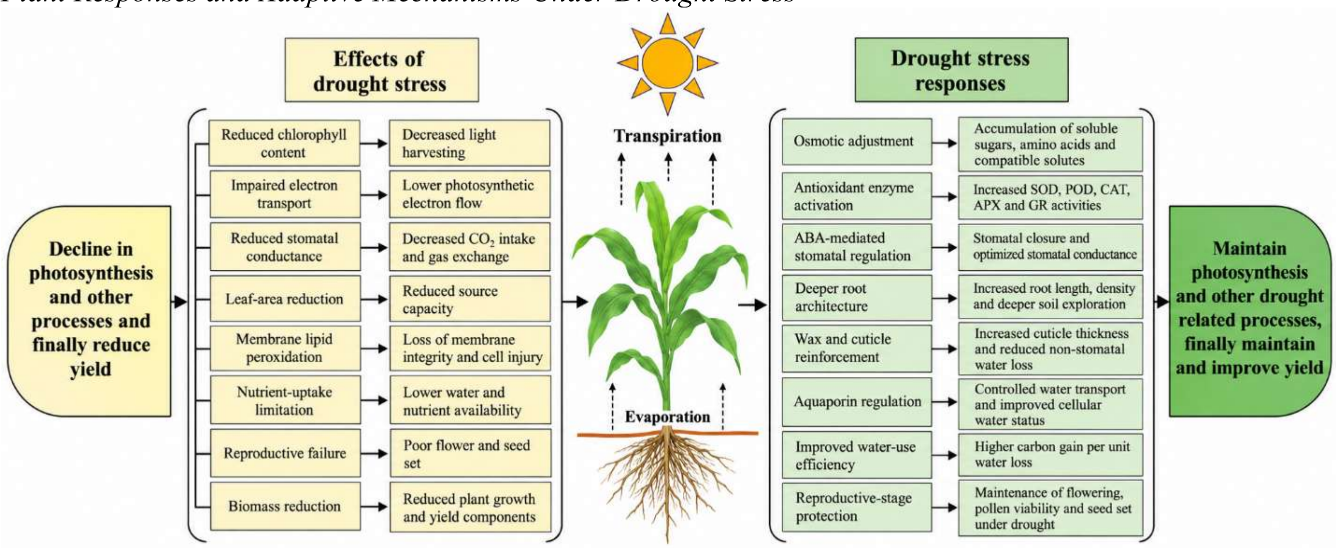
decisions regarding crop selection, planting, irrigation, fertilization, and harvesting. Institutional credit was included because liquidity limitations may prevent farmers from purchasing quality seed, irrigation equipment, and other productivity-enhancing inputs (Hossain et al., 2021). Insurance participation was considered because financial protection can encourage farmers to invest in improved but initially costly technologies. The analytical stages used to estimate and compare farm-level efficiency are illustrated in Figure 5. The procedure integrated production inputs, climatic conditions, and socioeconomic factors to estimate potential output and calculate farm-specific efficiency scores.

Figure 5

Plant Responses and Adaptive Mechanisms Under Drought Stress



Farm production and input records were first combined with climate and environmental observations. The frontier model then estimated the maximum feasible output for each farm under its observed operating conditions. Differences between potential and actual output were decomposed into random shocks and technical inefficiency. The resulting efficiency scores were subsequently linked with farm-level socioeconomic, institutional, and adaptation characteristics. Efficiency scores were compared between climate-resilient and conventional farms for the complete sample and separately across the four agroecological zones. Zone-specific comparisons were important because irrigation availability, soil quality, drought intensity, and production opportunities differed across locations (Adekanmbi & Olaniyi, 2026). Annual comparisons were also performed to determine whether efficiency gaps became larger during periods of severe climatic stress. Several diagnostic and robustness procedures were undertaken to verify the stability of the estimates. Alternative production specifications were examined, and the estimated results were compared across input definitions, agroecological zones, and adaptation-intensity groups. Multicollinearity among production inputs was evaluated, and extreme observations were checked against the original farm records. Likelihood-based tests were used to determine whether the inefficiency component was statistically meaningful and whether SFA was preferable to an ordinary average-response production model. The analysis further assessed the potential output gains available if inefficient farms moved closer to the production frontier.

This did not assume that all farms could immediately achieve complete efficiency; rather, it identified realistic opportunities for improving resource allocation under comparable production conditions. The results helped determine whether higher productivity required additional inputs or could be achieved through improved management of existing land, labor, water, fertilizer, and machinery resources (Cakmakci et al., 2025). SFA provided a comprehensive method for evaluating how effectively the sampled farms transformed agricultural inputs into marketable output. By separating uncontrollable climatic shocks from managerial

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inefficiency, the approach produced a fairer comparison of climate-resilient and conventional farms. It also clarified the roles of education, extension, credit, climate information, insurance, and adaptation intensity in strengthening farm-level productivity and resource-use efficiency.

4.4 Monte Carlo Simulation of Climate and Market Uncertainty

Monte Carlo simulation was employed to evaluate the economic performance of climate-resilient agriculture under uncertain climatic and market conditions. Conventional cost-benefit analysis generally relies on fixed average values, although actual farm outcomes vary according to rainfall, temperature, crop yield, input costs, output prices, maintenance requirements, and the occurrence of extreme weather events. The simulation addressed this limitation by repeatedly recalculating farm outcomes using alternative values drawn from predefined probability distributions. The principal simulation outputs included crop yield, climate-related yield loss, production cost, net farm income, income variability, net present value, and benefit-cost ratio. Separate simulations were conducted for climate-resilient and conventionally managed farms to compare their economic vulnerability under equivalent climate and market conditions. A total of 10,000 iterations was performed for each management system, providing a sufficiently broad range of possible production and financial outcomes (Ahmed et al., 2025). Probability distributions were assigned according to the nature and observed behavior of each uncertain input. Historical farm, meteorological, and market records were used to establish central values and plausible variation ranges. Normally distributed variables were used where observations fluctuated around a stable mean, while triangular distributions were applied when minimum, most-likely, and maximum values were available. Bounded distributions were used for variables expressed as proportions, such as crop-loss rates. The major simulation inputs and assumed uncertainty ranges are presented in Table 5.

Table 5

Principal Inputs and Uncertainty Assumptions Used in Monte Carlo Simulation

Uncertain input	Simulation range	Primary data source
Seasonal rainfall	−25% to +20%	Meteorological observations
Average temperature	+0.5 to +3.0°C	Meteorological observations
Crop yield	−30% to +20%	Farm production records
Climate-related crop loss	5--35%	Farm surveys and loss assessments
Farm-gate crop price	−15% to +25%	Market-price databases
Fertilizer cost	−5% to +30%	Purchase receipts and market records
Irrigation and energy cost	−5% to +35%	Irrigation and energy records
Labor cost	−10% to +20%	Household surveys and farm records
Maintenance cost	5--15% of investment cost	Equipment and farm records
Adaptation effectiveness	10--30% loss reduction	Comparative farm records
Discount rate	6--12%	Financial assumptions
Investment lifespan	8--15 years	Equipment and technology records

Zone-specific rainfall and temperature distributions were used because climatic exposure differed across the four agroecological zones. Similarly, crop-price and input-cost distributions were adjusted where important market differences existed among production locations. Correlations were incorporated between logically related variables, including rainfall and yield, temperature and irrigation demand, and energy prices and irrigation costs. The simulation procedure is illustrated in Figure 6. Climatic, production, and market variables were first assigned probability distributions. Random values were then drawn from these distributions and entered into the farm-economic model. Each iteration produced a new set of productivity, profitability, and investment outcomes. After 10,000 iterations, the resulting distributions were analyzed to determine expected values, variability, downside risk, and the probability of financially favorable outcomes.

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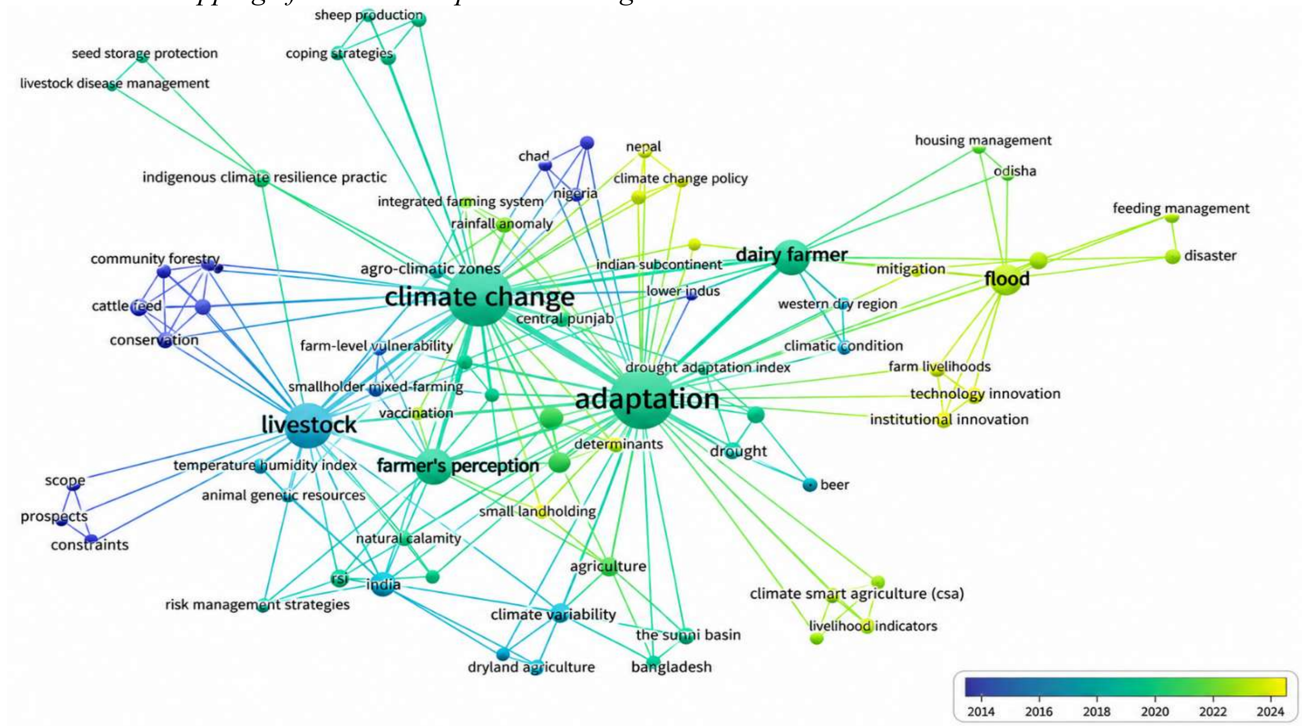
Figure 6

Bibliometric Mapping of Climate Adaptation and Agricultural Resilience Themes



The simulated outcomes were summarized using the mean, median, standard deviation, percentile intervals, and probability of falling below critical economic thresholds. Downside-risk measures included the probability of negative net farm income, a net present value below zero, and a benefit--cost ratio below one. The analysis also estimated the likelihood that climate-related yield losses would exceed acceptable levels under each management system. Lower probabilities of adverse outcomes indicated stronger economic and climatic resilience. Comparative distributions were generated for climate-resilient and conventional farms. This allowed the analysis to determine whether adaptation practices only increased expected profitability or also reduced the variability of possible outcomes (Bellmann, 2025). A narrower income distribution and lower probability of financial loss were interpreted as evidence of improved farm-income stability. Separate simulations across the four agroecological zones were conducted to identify locations where adaptation produced the greatest risk-reduction benefits. Sensitivity analysis was performed to identify the variables exerting the strongest influence on the simulation results. Changes in rainfall, temperature, crop yield, market price, fertilizer cost, irrigation cost, adaptation effectiveness, and the discount rate were examined individually and jointly.

Variables that produced the largest changes in net farm income and net present value were identified as priority areas for agricultural policy and farm-level risk management. Stress-testing scenarios were also incorporated into the simulation. These scenarios included severe drought, unusually high temperature, declining crop prices, increasing fertilizer costs, and simultaneous climate and market shocks (Kumar et al., 2023). The combined-shock scenario represented the most adverse condition because farms experienced both production losses and unfavorable price or cost movements. Comparing management systems under these conditions provided evidence regarding the capacity of integrated adaptation to protect production and income during extreme events. Monte Carlo simulation strengthened the economic evaluation by explicitly incorporating climate and market uncertainty. It generated probability-based evidence regarding profitability, income stability, investment feasibility, and potential yield losses. The approach therefore supported a more realistic comparison of climate-resilient and conventional agriculture and provided decision-relevant information for farmers, policymakers, lenders, insurers, and agricultural-development organizations.

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4.5 Future Climate and Yield-Loss Scenario Modeling

Future climate and yield-loss scenario modeling was conducted to assess how climate-resilient and conventional farms could perform under progressively changing climatic conditions. The analysis extended the historical three-year panel dataset by combining observed relationships among rainfall, temperature, irrigation demand, vegetation stress, crop yield, and production costs with alternative climate assumptions. This approach enabled the study to estimate future vulnerability rather than evaluating adaptation performance exclusively under past conditions. Three principal climate scenarios were constructed: reference conditions, moderate climate stress, and severe climate stress. The reference scenario represented climatic conditions close to the observed historical average (Zheng et al., 2026). The moderate-stress scenario reflected higher temperatures, reduced and increasingly irregular rainfall, greater irrigation requirements, and more frequent dry periods. The severe-stress scenario represented prolonged drought, intense heat, substantial rainfall reduction, higher water and energy costs, and a greater probability of crop damage. The parameters used to differentiate these scenarios are presented in Table 6.

Table 6

Climatic and Agricultural Assumptions Used in Future Yield-Loss Scenarios

Scenario variable	Reference conditions	Moderate climate stress	Severe climate stress
Average temperature change	0 to +0.5°C	+1.0 to +2.0°C	+2.0 to +3.5°C
Seasonal rainfall change	−5% to +5%	−10% to −20%	−20% to −35%
Rainfall variability	Historical average	10--20% increase	20--40% increase
Drought frequency	Historical average	One additional event within 3--5 years	One additional event within 1--3 years
Irrigation demand	Baseline requirement	10--20% increase	20--40% increase
Soil-moisture availability	Normal seasonal range	10--20% reduction	20--35% reduction
Heat-stress days	Historical average	10--20% increase	25--45% increase
Pest and disease pressure	Baseline level	5--15% increase	15--30% increase
Input-cost pressure	Historical trend	10--20% increase	20--35% increase

The reference scenario provided the benchmark against which future changes were measured. It preserved rainfall, temperature, production costs, and extreme-event frequency close to their observed averages. This scenario established the expected performance of both farm-management systems in the absence of substantial additional climate pressure. It also allowed yield and income differences attributable to existing management practices to be distinguished from those caused by future climatic deterioration. Under the moderate-stress scenario, average temperature was assumed to increase while seasonal rainfall declined and became more variable. Irrigation requirements, energy expenditures, and the frequency of dry periods were also increased. Under the severe-stress scenario, these changes were intensified and combined with greater soil-moisture deficits, heat-stress days, pest pressure, and input costs (Padaria et al., 2026). The severe scenario consequently represented a compound-risk environment in which climatic and economic shocks occurred simultaneously. The complete scenario-modeling process is illustrated in Figure 7. Historical data and future climate assumptions were first integrated into the production model. Climate effects were then transmitted through soil moisture, irrigation demand, crop stress, and input costs. Separate adaptation-response parameters were applied to climate-resilient and conventional farms before projected yield and income losses were compared.

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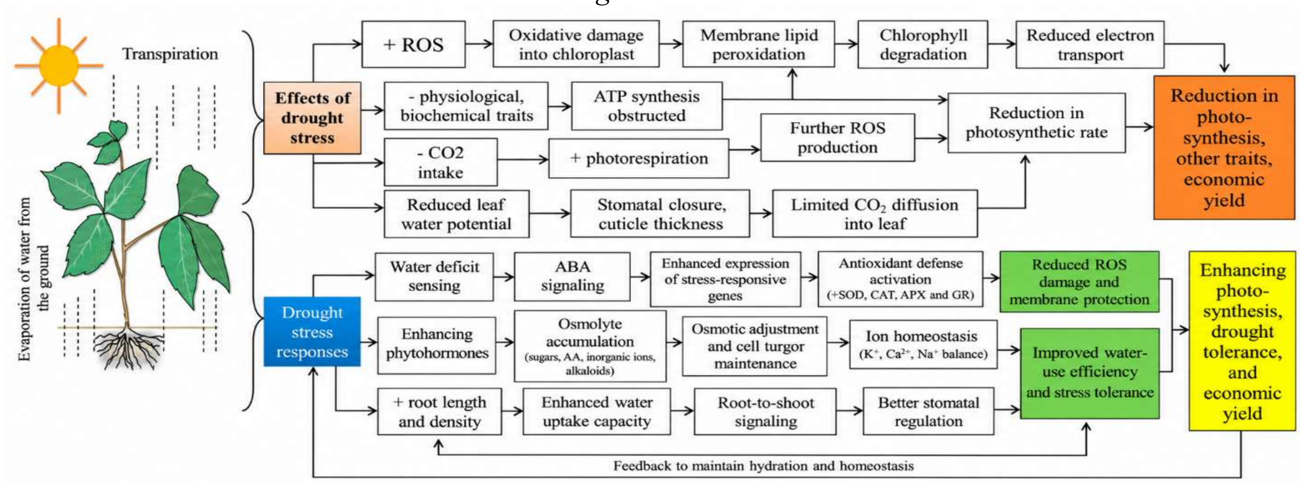
Figure 7

Future Climate and Yield-Loss Scenario-Modeling Framework



Climatic changes were not assumed to influence yield directly through a single pathway. Reduced rainfall affected soil-moisture availability and irrigation demand, whereas higher temperatures increased evapotranspiration and the risk of heat damage during sensitive crop-growth stages. Extreme events additionally influenced crop survival, input requirements, and marketable output. These relationships were incorporated into production and economic models to estimate changes in yield, costs, and income. Separate response parameters were specified for climate-resilient and conventional farms. For climate-resilient farms, the model incorporated the protective effects of drought-tolerant varieties, crop diversification, conservation tillage, precision irrigation, soil-fertility management, agroforestry, and weather-indexed insurance (Talbi et al., 2024). These interventions were expected to improve moisture retention, reduce water demand, distribute production risk, maintain crop health, and limit financial losses. Conventional farms were modeled with lower adaptive capacity because they had fewer mechanisms for managing climatic stress. Projected yield loss was measured relative to the expected output under reference conditions. The model compared potential yield with the marketable output estimated under each climate scenario. Losses arising from drought, excessive heat, rainfall irregularity, flooding, soil-moisture limitation, and pest pressure were expressed as a percentage of reference yield.

Similar comparisons were performed for net farm income, irrigation expenditure, total production costs, and income variability. The scenario results were evaluated for the complete sample and separately across agroecological zones (Ginigaddara & Kodithuwakku, 2024). This disaggregated assessment allowed the study to identify whether drought-prone, rainfall-dependent, irrigated, or highly climate-variable zones experienced different levels of future risk. It also helped determine which adaptation packages were most suitable under particular environmental and resource conditions. Sensitivity analysis was performed by changing major scenario assumptions individually and collectively. Temperature increases, rainfall reductions, crop-price variation, irrigation costs, fertilizer prices, and adaptation effectiveness were adjusted to determine their influence on projected yield and income losses. Particular attention was given to compound-risk scenarios in which severe climatic conditions occurred alongside rising input costs or declining output prices. The reliability of the projections was assessed by comparing model-generated outcomes with observed farm responses during historically adverse seasons. Alternative climate ranges and production-response assumptions were also evaluated to determine whether the conclusions remained stable. The scenario results were interpreted as conditional projections rather than exact forecasts because future agricultural outcomes would also depend on technological development, policy support, farmer behavior, and market conditions.

5. Results and Discussion

The empirical findings demonstrated substantial differences between climate-resilient and conventionally managed farms in terms of agricultural productivity, resource-use efficiency, profitability, income stability, technical efficiency, and exposure to climate-related losses. Across the four agroecological zones, farms adopting an integrated package of climate-resilient practices generally performed better than conventional farms. These improvements were associated with the combined adoption of drought-tolerant crop varieties, crop diversification, conservation tillage, precision irrigation, integrated soil-fertility management, agroforestry, weather-indexed crop insurance, and climate-information services. Climate-resilient farms achieved an average crop yield of 5.84 t/ha, compared with 4.63 t/ha among conventionally managed farms. This difference represented a 26.1% improvement in agricultural productivity. The higher yield suggests that climate-resilient strategies strengthened the ability of crops to withstand moisture shortages, irregular rainfall, elevated temperatures, and soil-quality limitations. Drought-tolerant varieties helped maintain plant growth under water stress, while conservation tillage and residue retention improved soil-moisture availability.

Precision irrigation ensured that limited water resources were delivered according to crop requirements, and crop diversification reduced dependence on a single climate-sensitive crop. The results further showed that water-use efficiency increased by 29.4% under climate-resilient management (Tariqul Islam et al., 2026). This improvement was particularly important in the drought-prone and water-stressed zones, where irrigation availability represented a major constraint on production. Precision irrigation reduced losses from evaporation, runoff, and excessive application, while improved soil management enhanced infiltration and moisture retention. The combined influence of irrigation technology and soil conservation enabled climate-resilient farms to generate more output from each unit of water. Fertilizer consumption decreased by 17.8% among climate-resilient farms. Importantly, this reduction occurred alongside higher crop yields, indicating that improved performance was not achieved through increased chemical input consumption. Integrated soil-fertility management, soil testing, organic amendments, residue incorporation, crop rotation, and targeted nutrient application enhanced the efficiency of fertilizer use.

These practices allowed nutrients to be applied more accurately according to soil and crop requirements, reducing unnecessary expenditure and limiting the environmental consequences of excessive fertilizer application. Climate-related crop losses were 24.6% lower under climate-resilient management. The reduction reflected the protective and complementary effects of multiple adaptation practices. Improved crop varieties-maintained productivity during drought and heat stress, crop diversification distributed production risks, conservation tillage protected soil against erosion, and agroforestry moderated temperature and wind exposure. Access to climate information also allowed farmers to adjust planting, irrigation, input application, and harvesting schedules according to expected weather conditions. The comparative results are summarized in Table 7.

Table 7

Comparative Performance of Climate-Resilient and Conventional Farms

Performance indicator	Climate-resilient farms	Conventional farms	Comparative change
Average crop yield	5.84 t/ha	4.63 t/ha	+26.1%
Water-use efficiency	Improved level	Baseline level	+29.4%
Fertilizer consumption	Reduced level	Baseline level	−17.8%
Climate-related crop losses	Reduced level	Baseline level	−24.6%
Net farm income	US$2,986/ha	US$2,214/ha	+34.9%
Income variability	Lower variability	Baseline variability	−21.7%

The increase in agricultural productivity was accompanied by reductions in resource consumption and climate-related losses. This is an important result because higher output in conventional systems is frequently obtained through greater use of irrigation water, fertilizer, energy, and other production inputs. In the present study, climate-resilient farms achieved higher yields while using critical resources more efficiently. The findings therefore demonstrate that climate adaptation can support agricultural productivity and environmental sustainability simultaneously. The stochastic frontier analysis indicated that climate-resilient farms operated closer to the estimated production frontier than conventionally managed farms. This finding

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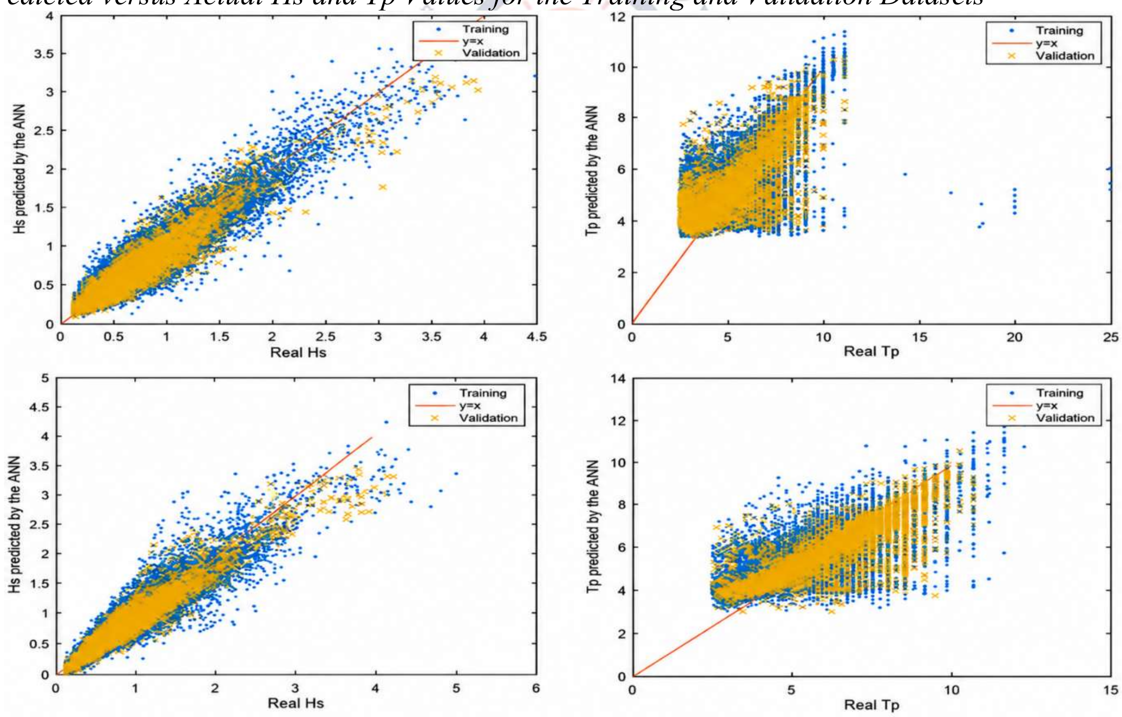
suggests that their productivity advantage was not caused solely by greater input use. Instead, climate-resilient farmers transformed available land, labor, water, seed, fertilizer, machinery, and energy into marketable crop output more effectively. The distinction between random shocks and inefficiency was particularly important because agricultural output was influenced by weather and other conditions beyond farmers' direct control. The efficiency advantage of climate-resilient farms became more visible during unfavorable climatic conditions.

Under relatively normal weather, both groups were able to maintain acceptable production. However, when rainfall became irregular, temperatures increased, or water supplies declined, conventional farms experienced a greater reduction in output relative to the inputs applied. Climate-resilient farms maintained comparatively stronger performance because their production systems contained multiple mechanisms for protecting soil, conserving water, supporting plant health, and distributing production risk. The inefficiency analysis also showed that education, farming experience, agricultural extension, institutional credit, climate information, and insurance participation influenced farm-level efficiency. Farmers with access to technical guidance were better positioned to select suitable varieties, apply water and fertilizer efficiently, and respond to emerging climatic stress. Institutional credit enabled timely purchase of quality seeds and other essential inputs, while climate information supported improved planting, irrigation, and harvesting decisions. These findings demonstrate that efficient resource use depends on both agricultural technology and the socioeconomic capacity of farmers to implement it correctly.

Figure 8

ANN-Predicted versus Actual Hs and Tp Values for the Training and Validation Datasets



The figure 8 compares the artificial neural network (ANN) predictions with the actual significant wave height (Hs) and peak wave period (Tp) values for the training and validation datasets. The close distribution of most data points around the y= xy reference line indicates strong agreement between the predicted and observed values, particularly for Hs. Greater dispersion is visible for Tp at higher values, suggesting comparatively higher prediction uncertainty and the influence of extreme observations. Overall, the similar patterns in the training and validation results demonstrate satisfactory model accuracy, consistency, and generalization capability. Average net farm income reached US$2,986/ha under climate-resilient management, compared with US$2,214/ha under conventional farming. The difference of US$772/ha represented a 34.9% income advantage. The improvement in income was proportionally greater than the increase in crop yield, suggesting that climate-resilient management affected both farm revenue and production costs. Higher marketable output increased gross revenue, while reductions in irrigation, fertilizer, energy, and climate-loss expenses lowered total production expenditure. Crop diversification and agroforestry contributed to profitability by creating additional sources of farm revenue and reducing dependence on a single crop. When one crop was negatively affected by drought, heat, pests, or market-price decline, income from other crops or tree-based products helped compensate for the loss. This portfolio effect strengthened the overall economic performance of climate-resilient farms and reduced their vulnerability to individual production and market shocks. Income variability declined by 21.7% among climate-resilient farms, indicating that their financial outcomes were more stable over the three-year period. This finding is important because higher average income alone does not guarantee resilience. Farms experiencing severe year-to-year fluctuations may still struggle to purchase inputs, repay loans, support household consumption, and invest in subsequent production cycles. Lower income variability therefore demonstrated that climate-resilient farms achieved not only greater profitability but also improved financial security.

Figure 9

Acceleration Time-History Record and Its Corresponding Amplitude Envelope

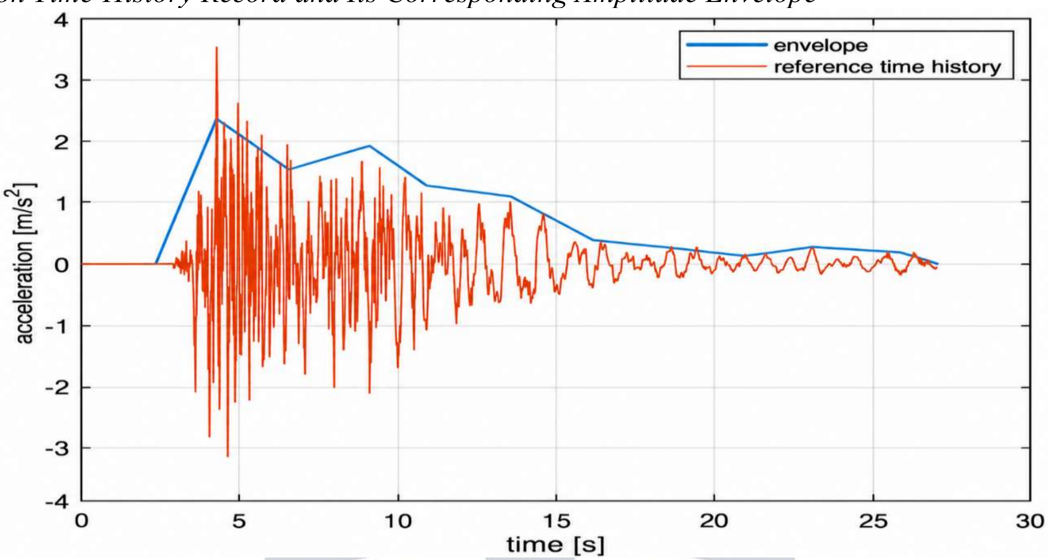


Figure 9 presents the variation in acceleration over time, together with the corresponding upper-amplitude envelope. The reference time history shows strong transient oscillations between approximately 3 and 10 s, followed by a gradual reduction in amplitude. The envelope captures this decay pattern and indicates that the structural or ground-motion response approaches a stable level after nearly 20 s. The fixed-effects regression analysis identified irrigation efficiency, crop diversification, soil-health management, access to climate information, agricultural extension, and institutional credit as significant determinants of profitability and resilience. Irrigation efficiency improved farm income by supporting crop growth while lowering water and energy expenditure. Crop diversification distributed production and market risks, while soil-health management improved moisture retention, nutrient availability, and long-term land productivity. These relationships remained meaningful after controlling stable differences among farms and common yearly changes (Roohi et al., 2025). Access to climate information improved farmers' ability to respond to expected rainfall and temperature conditions. Timely weather forecasts supported appropriate decisions regarding crop selection, planting dates, irrigation, fertilizer application, and harvesting. Agricultural extension strengthened technical knowledge and facilitated the correct use of climate-resilient practices. Institutional credit reduced financial constraints and allowed farms to invest in irrigation systems, improved seeds, conservation equipment, and other productivity-enhancing technologies. The findings confirm that climate resilience is shaped by institutional support as well as physical farm practices.

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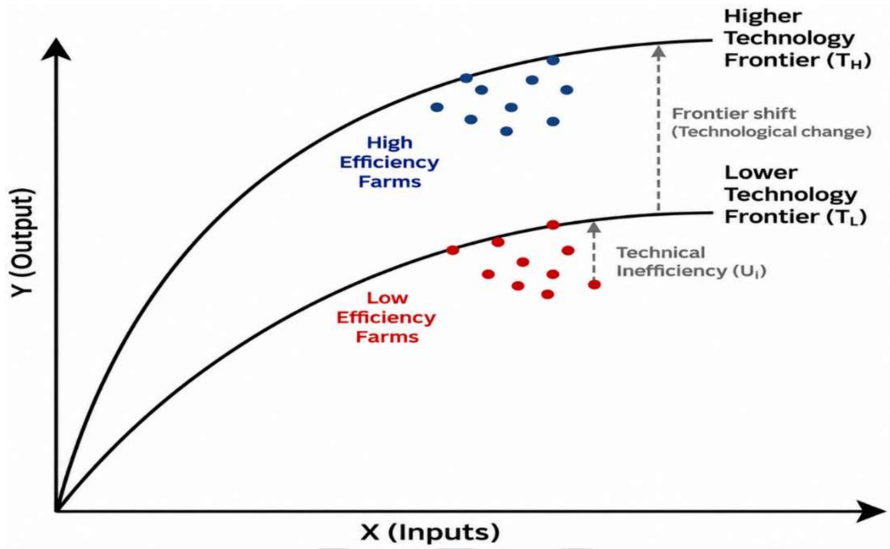
Figure 10

Stochastic Production Frontiers Illustrating Farm Efficiency, Technical Inefficiency, and Technological Change



The figure 10 compares farms operating under lower and higher technology frontiers. Blue points represent high-efficiency farms located near the higher frontier, whereas red points indicate relatively low-efficiency farms below the lower frontier. The discounted cost--benefit analysis demonstrated that the integrated adaptation package was financially feasible. A benefit--cost ratio of 1.89 indicated that every US$1.00 invested generated approximately US$1.89 in discounted benefits. The net present value reached US$3,764/ha, confirming that the present value of additional revenues, resource savings, and avoided climate losses exceeded the investment and operating costs. The integrated adaptation package produced an internal rate of return of 28.6%, indicating an attractive return relative to the applied discount rate. The estimated payback period was 2.7 years, suggesting that farmers could recover the initial investment within approximately three production years. The principal financial outcomes are shown in Table 8.

Table 8

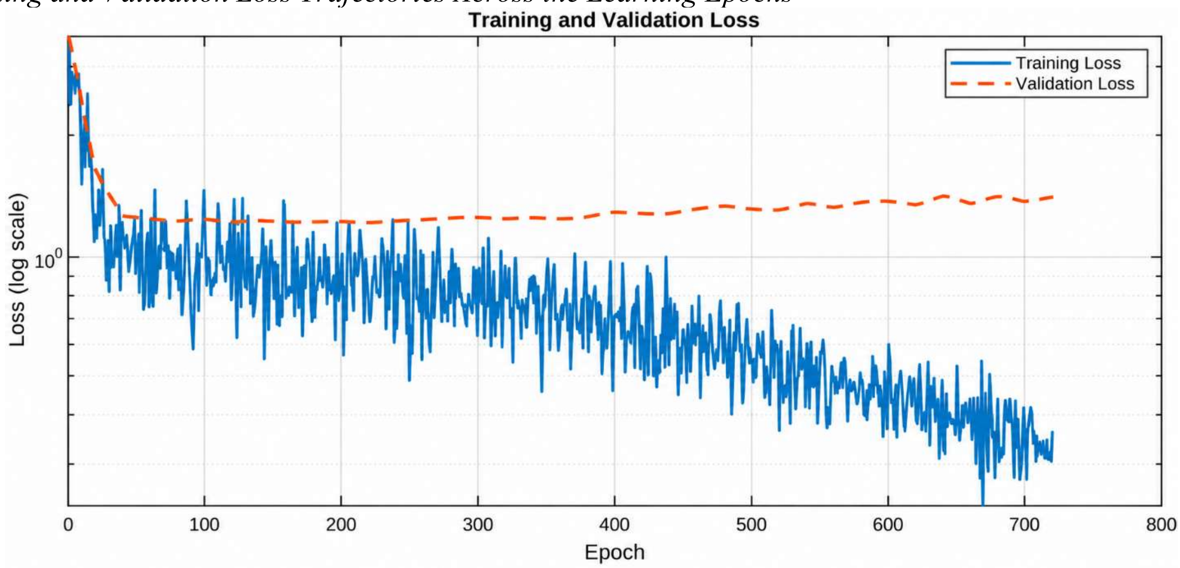
Financial Feasibility of the Integrated Climate-Resilient Adaptation Package

Financial indicator	Estimated value	Decision criterion
Benefit--cost ratio	1.89	Greater than 1.00
Net present value	US$3,764/ha	Greater than US$0
Internal rate of return	28.6%	Greater than discount rate
Payback period	2.7 years	Shorter period preferred
Net-income advantage	34.9%	Positive difference preferred
Income-variability reduction	21.7%	Lower variability preferred

The indicators reported in Table 8 collectively support the economic viability of climate-resilient agriculture. Nevertheless, the payback period shows that farmers must finance establishment costs before obtaining the complete economic benefits. This can create a significant barrier for smallholders with limited savings and restricted access to formal credit. Equipment-sharing arrangements, low-interest financing, targeted subsidies, and flexible repayment programs may therefore be necessary to increase adoption. Monte Carlo simulation showed that the economic advantages of climate-resilient agriculture remained comparatively stable under uncertainty in rainfall, temperature, crop yields, output prices, fertilizer costs, labor expenses, irrigation requirements, and energy prices. Climate-resilient farms exhibited a lower probability of severe income loss and a greater likelihood of maintaining positive returns. Figure 11 illustrates the model's training and validation losses on a logarithmic scale. Training loss decreases progressively with continued fluctuations, indicating effective learning and improved fitting. In contrast, validation loss initially declines but then gradually increases after approximately 100 epochs. The widening gap between the two curves suggests overfitting, indicating that early stopping or stronger regularization may improve the model's generalization performance.

Figure 11

Training and Validation Loss Trajectories Across the Learning Epochs



This result confirms that adaptation improved both expected profitability and protection against unfavorable outcomes. Yield, rainfall, output prices, irrigation expenses, and adaptation effectiveness were among the most influential sources of uncertainty. Reduced rainfall increased irrigation requirements and energy costs, while higher temperatures intensified crop-water demand and heat stress. Declining output prices lowered gross revenue even when crop production remained stable. Effective adaptation moderated these risks by limiting yield reductions and controlling production expenses. The economic value of climate-resilient practices became more pronounced as climatic conditions worsened. Under reference conditions, differences between the management systems were primarily associated with input efficiency and operating costs. Under moderate and severe climate stress, avoided crop losses and income stabilization became increasingly important. This demonstrates that evaluating adaptation only under average climatic conditions may underestimate its total economic value. Future scenario modeling indicated that integrated adaptation could restrict projected climate-induced yield losses to 8.6%, compared with 23.9% under conventional farming. The difference of 15.3 percentage points means that adaptation reduced projected yield damage by approximately 64% relative to the conventional loss level. This substantial reduction demonstrated the capacity of integrated practices to protect food production under increasingly difficult climatic conditions. Conventional farms were more vulnerable to the combined effects of rainfall reduction, rising temperature, soil-moisture deficits, greater irrigation demand, and increasing production costs.

Climate-resilient farms were able to absorb a larger share of these pressures because risk was distributed across several complementary measures. Drought-tolerant varieties supported plant survival, precision irrigation increased water productivity, conservation tillage improved soil-moisture retention, crop diversification reduced production concentration, and agroforestry strengthened ecological protection. Weather-indexed insurance did not prevent physical crop damage but reduced its financial consequences and supported recovery following severe events. Figure 12 compares total energy-use intensity (EUI) with heating, interior lighting, electric equipment, water systems, and cooling consumption across 200 cases. Cooling represents the largest end-use component and largely determines variations in overall EUI, while water systems and electric equipment contribute moderately. Heating remains comparatively low in most cases. The

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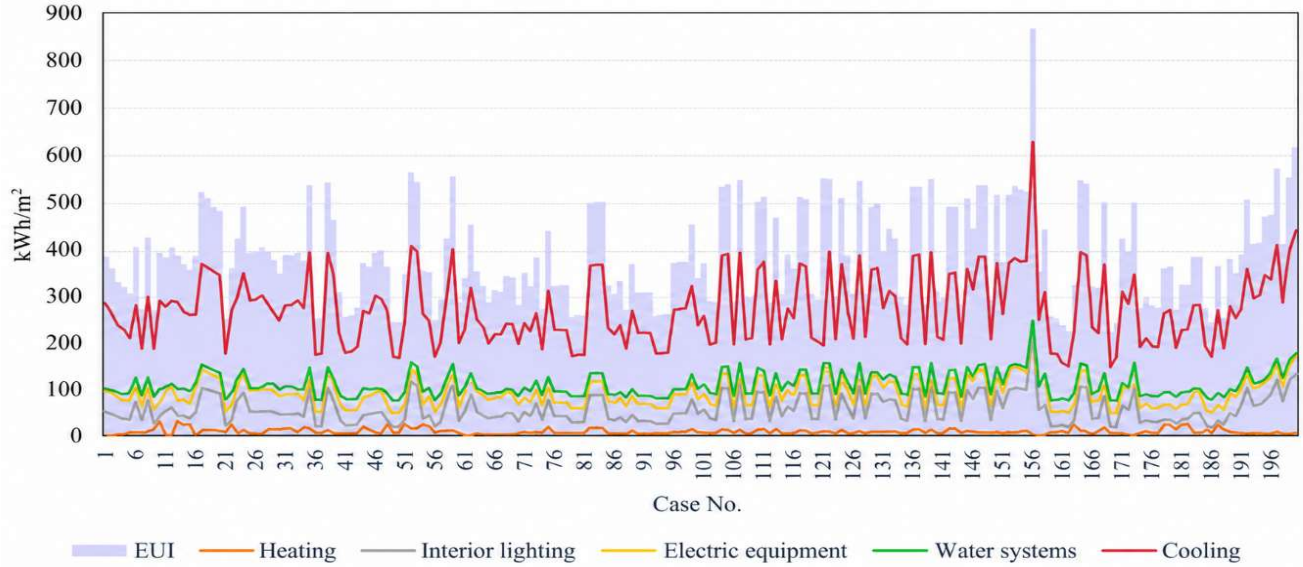
pronounced peak near Case 156 indicates an exceptionally energy-intensive case, primarily associated with increased cooling and water-system demand.

Figure 12

End-Use Consumption Profiles Across the Selected Cases



The overall results confirm that climate-resilient agriculture generated mutually reinforcing productive, environmental, and financial benefits. The 26.1% increase in crop yield, 29.4% improvement in water-use efficiency, 17.8% reduction in fertilizer consumption, and 24.6% decline in climate-related crop losses demonstrate that adaptation enhanced food production while conserving limited resources. The 34.9% increase in net income and 21.7% reduction in income variability further confirm that these improvements translated into stronger and more stable financial performance. The findings additionally emphasize the importance of integrated adoption. No individual intervention can address every dimension of climatic and economic risk. Improved crop varieties protect plants against drought and heat, irrigation technologies manage water scarcity, conservation tillage protects soil, diversification distributes production risk, agroforestry improves ecological functions, and insurance limits financial exposure. Their coordinated use establishes a more comprehensive resilience system than isolated adoption. However, the successful expansion of climate-resilient agriculture requires more than evidence of positive financial returns. High initial costs, limited availability of improved seeds, inadequate equipment, weak extension systems, and restricted access to climate information can prevent farmers from adopting beneficial practices. Policy interventions should consequently integrate affordable finance, extension training, local demonstration projects, irrigation investment, crop insurance, climate-information platforms, and market-development support.

6. Future Work

Future research should expand the geographical and temporal coverage of the study to capture a wider range of climatic conditions, cropping systems, soil characteristics, and socioeconomic environments. Although the present analysis used a three-year panel dataset covering 480 farms across four agroecological zones, longer observation periods would provide stronger evidence regarding the durability of productivity gains, soil-health improvements, investment returns, and income stability. Future studies should also include more regions and farm categories to determine whether the identified benefits remain consistent across small, medium, and large-scale agricultural systems. Further research should examine the independent and combined effects of individual climate-resilient practices. The current study evaluated an integrated package consisting of drought-tolerant varieties, crop diversification, conservation tillage, precision irrigation, integrated soil-fertility management, agroforestry, and weather-indexed crop insurance. Future analyses could identify which combinations generate the greatest economic return under specific climatic and agroecological conditions.

Such evidence would support location-specific adaptation packages and prevent farmers from investing in technologies that are unsuitable for their soils, water resources, crop portfolios, or financial capacity (Singh & Rao, 2023).

Future modeling frameworks should incorporate higher-resolution climate projections, real-time weather observations, satellite imagery, soil sensors, Internet of Things devices, and remote-sensing indicators. These technologies could improve the early detection of drought, heat stress, crop disease, irrigation deficiencies, and vegetation decline. Machine-learning methods could also be combined with economic models to generate more accurate forecasts of crop yield, input demand, farm income, and climate-related losses. Such systems could provide farmers with timely recommendations concerning crop selection, planting dates, irrigation schedules, fertilizer application, and harvesting. Greater attention should also be given to the long-term economic value of soil health, biodiversity, groundwater conservation, carbon sequestration, and ecosystem restoration. These benefits are not always fully reflected in annual farm revenue, although they influence the productive capacity and environmental sustainability of agriculture. Future cost-benefit analyses should therefore incorporate the monetary value of ecosystem services and avoided environmental damage (Dumont, 2019). This would provide a more complete assessment of the social and economic returns generated by conservation tillage, agroforestry, crop rotation, and integrated soil management.

Additional studies are needed to evaluate the distributional effects of climate-resilient agriculture. Adoption opportunities and outcomes may differ according to farm size, household income, land ownership, gender, education, age, access to irrigation, and institutional support. Future research should examine whether resource-constrained and tenant farmers receive benefits comparable to those obtained by larger or wealthier producers. This evidence could support the development of inclusive credit, subsidy, training, and insurance programs. The design and effectiveness of weather-indexed crop insurance also require further investigation. Future work should examine basis risk, premium affordability, farmer trust, payment speed, weather-station coverage, and the use of satellite information for loss verification. Insurance products could be integrated with climate-resilient loans, improved seeds, extension services, and digital climate information. Such bundled programs may improve adoption while providing stronger protection against severe climatic shocks. Finally, future research should develop dynamic decision-support systems that integrate agricultural, climatic, market, and financial information. These systems could continuously update adaptation recommendations such as rainfall forecasts, water availability, input prices, crop conditions, and market opportunities change. Participatory research involving farmers, extension specialists, financial institutions, insurers, and policymakers would be essential for ensuring that such tools are practical, affordable, transparent, and responsive to local agricultural needs.

7. Conclusion

This study developed an integrated economic modeling framework to evaluate the contribution of climate-resilient agriculture to sustainable food production, efficient resource utilization, and farm-income stability. Using a three-year panel dataset covering 480 farms across four agroecological zones, the analysis compared 240 climate-resilient farms with 240 conventionally managed farms. The framework combined descriptive statistics, fixed-effects panel regression, stochastic frontier analysis, cost--benefit analysis, and Monte Carlo simulation to examine productivity, profitability, technical efficiency, investment feasibility, and climate-risk exposure.

The findings demonstrated that climate-resilient farms achieved an average crop yield of 5.84 t/ha, compared with 4.63 t/ha for conventional farms, representing a 26.1% improvement. Water-use efficiency increased by 29.4%, while fertilizer consumption and climate-related crop losses declined by 17.8% and 24.6%, respectively. These results confirm that higher agricultural productivity can be achieved alongside more efficient use of water, nutrients, and other production resources. Climate-resilient management also produced significant economic benefits. Average net farm income reached US$2,986/ha, compared with US$2,214/ha under conventional production, resulting in a 34.9% income advantage. Income variability declined by 21.7%, indicating that adaptation improved not only profitability but also financial stability. The integrated adaptation package was economically feasible, producing a benefit-cost ratio of 1.89, a net present value of US$3,764/ha, an internal rate of return of 28.6%, and a payback period of 2.7 years. The analysis further identified irrigation efficiency, crop diversification, soil-health management, climate-information access, agricultural extension, and institutional credit as important drivers of profitability and resilience. Scenario modeling showed that integrated adaptation could restrict projected climate-induced losses to 8.6%, compared with 23.9% under conventional farming.

This finding demonstrates the capacity of coordinated adaptation practices to protect agricultural production as climatic pressures intensify. Overall, climate-resilient agriculture represents an environmentally sustainable and economically viable pathway for strengthening food security and rural livelihoods. However, its widespread adoption requires coordinated support through affordable credit, extension services, improved seed systems, precision-irrigation infrastructure, accessible crop insurance, and reliable climate-information platforms. Public institutions, financial organizations, researchers, insurers, and farming communities should therefore collaborate to develop locally appropriate adaptation packages. Such coordinated investment can increase food production, stabilize farm income, conserve critical resources, and strengthen the long-term resilience of agricultural systems under a changing climate.

Author Contributions

All authors participated in ideation, development, and writing the manuscript. All authors read and approved the final manuscript.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this article.

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Informed Consent

Not applicable. This study did not involve human participants requiring informed consent. The data used in this research were obtained from anonymized financial records with all personally identifiable information removed. No private or sensitive information was collected from individuals.

Data Availability

The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request. Due to privacy and confidentiality considerations, raw financial data may not be publicly distributed but can be accessed through the corresponding author with appropriate data use agreements and institutional approvals. The authors are committed to transparency and will provide detailed methodological information, model specifications, and analysis protocols upon request.

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