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Article

Beyond Climate Shocks: Institutional and Technological Determinants of Agricultural Resilience and Sustainability in Semi-Arid South India

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Abstract: Agricultural systems in the semi-arid regions of South India are increasingly vulnerable to climatic variability, characterized by erratic monsoon patterns and rising temperature trends. Understanding the interaction between climatic stress and farm-level socioeconomic conditions is essential for assessing agricultural sustainability. This study examines the relationship between climate variability, institutional access, technological adoption, and agricultural sustainability in the Vellore district of Tamil Nadu. The analysis integrates 19 years of climatic data (2001–2019) with primary survey data collected from 200 farm households across 20 villages. A multidisciplinary analytical framework, combining Mann–Kendall trend analysis, Sen's slope estimation, fractional logit modeling, binary logistic regression, and a Principal Component Analysis (PCA)-based Sustainability Composite Index, is employed to examine both climatic trends and farm-level adaptive responses.
The results reveal substantial inter-annual rainfall variability with no statistically significant decline in Southwest Monsoon precipitation, while both maximum and minimum temperatures exhibit significant warming trends. Econometric analysis indicates that crop diversification decisions are primarily influenced by technology adoption and access to extension services rather than direct climatic variability. Similarly, technology adoption is strongly driven by institutional access and household income, suggesting that farmers adopt innovations as part of long-term productivity strategies rather than short-term responses to climatic shocks. The Sustainability Composite Index further identifies technology adoption, extension access, and farm income as the most significant determinants of resilience, while diversification contributes moderately to sustainability outcomes.
Overall, the findings indicate that resilience in semi-arid agricultural systems is shaped more strongly by institutional and technological factors than by climatic variability alone. These results underscore the importance of strengthening rural extension networks, promoting climate-smart technologies, improving irrigation access, and developing localized climate-risk management strategies. By integrating climatic trend analysis with farm-level socioeconomic data, this study provides district-level empirical evidence on the mechanisms through which institutional capacity mediates climate impacts on agriculture in semi-arid South India.
Keywords: climate variability; crop diversification; technology adoption; sustainability; fractional logit; principal component analysis.

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1. Introduction:

Agriculture in the semi-arid regions of South India is increasingly vulnerable to climatic uncertainties resulting from erratic monsoon patterns, rising temperature extremes, and escalating pressure on water resources. Over the past two decades, climate variability has emerged as a significant constraint to agricultural sustainability, particularly in regions where farming systems are heavily reliant on rainfall and where institutional support systems are unevenly distributed. These climatic changes have profound implications for agricultural productivity, rural incomes, and the long-term stability of livelihoods in smallholder farming systems.

The Vellore district of Tamil Nadu exemplifies a typical semi-arid agricultural economy characterized by variable rainfall, high temperature regimes, and increasing resource constraints. Agriculture in this region depends on both the Southwest Monsoon (June–September) and the Northeast Monsoon (October–December), yet the timing and distribution of rainfall across these seasons have become increasingly unpredictable. Such variability exposes farmers to production risks, crop failures, and income fluctuations, particularly for small and marginal farmers who possess limited financial and technological resources.

From an economic perspective, climate variability affects agricultural systems through multiple pathways. Beyond direct impacts on crop yields, climatic fluctuations influence farmers' investment decisions, cropping patterns, and resource allocation strategies. Rising temperatures can alter crop phenology and increase irrigation requirements, while irregular rainfall patterns reduce input efficiency and heighten production uncertainty. Consequently, understanding the interaction between climatic stress and socioeconomic adaptation mechanisms has become central to the study of agricultural sustainability in semi-arid regions. A growing body of literature underscores the importance of adaptive strategies such as crop diversification, technological innovation, and institutional support in mitigating climate-induced agricultural risks. Crop diversification allows farmers to spread production risk across multiple crops, while technology adoption—including improved seed varieties, micro-irrigation systems, and climate-smart practices—enhances resource efficiency and productivity stability. Equally important are institutional mechanisms such as extension services, credit access, and farmer cooperatives, which facilitate knowledge dissemination and enable farmers to implement adaptive strategies.

Despite the growing body of research on climate–agriculture interactions in India, numerous studies predominantly concentrate on either the biophysical impacts of climate or macro-level economic assessments. Such approaches frequently neglect the micro-level socioeconomic mechanisms that shape farmers' adaptive behaviors and influence the efficacy of adaptation strategies. Notably, there is a paucity of empirical research that concurrently examines climatic variability, institutional access, technological adoption, and farm-level sustainability outcomes within district-level agricultural systems in Tamil Nadu.

This study seeks to address this gap by developing an integrated climate–economics framework to analyze agricultural sustainability in the Vellore district. By integrating long-term climatic observations with farm-level socioeconomic data from 200 farmers across 20 villages, the research investigates how climatic variability influences crop diversification, technology adoption, and sustainability outcomes. The study employs a multidisciplinary analytical approach, incorporating Mann–Kendall trend analysis, Sen's slope estimation, econometric regression models, and a Principal Component Analysis (PCA)-based Sustainability Composite Index.

The study makes four significant contributions to the literature. First, it provides district-level empirical evidence from a semi-arid agricultural system in South India by integrating climatic trend analysis with farm-level socioeconomic data. Second, it elucidates the indirect pathways through which climate variability affects agricultural outcomes by identifying the mediating roles of institutional access and technological adoption. Third, it develops a multidimensional Sustainability Composite Index that captures economic, technological, social, and cognitive dimensions of resilience. Finally, the study offers policy-relevant insights into how institutional strengthening and technological diffusion can enhance climate resilience in smallholder farming systems.

2. Literature review:

2.1 Climate Variability and Agricultural Productivity

Climate variability has emerged as a critical challenge impacting agricultural productivity and rural livelihoods globally. Alterations in temperature patterns, rainfall variability, and the increasing frequency of extreme weather events have significant implications for crop yields and farm income, particularly in semi-arid regions. Research indicates that rising temperatures and erratic rainfall patterns directly influence crop growth cycles, soil moisture availability, and water resources, thereby heightening the vulnerability of agricultural systems(1).

Empirical studies conducted in developing countries reveal that climatic shocks often result in fluctuations in agricultural productivity and farm income. For instance,(1)demonstrated that climate change has already led to measurable yield reductions in several major crops across developing regions.

Similarly,(2)emphasized that climate variability poses a serious threat to global food security by affecting crop yields and increasing production risks, particularly in rainfed agricultural systems. These impacts are anticipated to be more pronounced in semi-arid tropical regions where agriculture is heavily reliant on rainfall and natural climatic conditions. In India, agricultural systems are particularly susceptible to climate variability due to the large proportion of rainfed farming and the dependence of rural livelihoods on agriculture. Rainfall variability and increasing temperature trends have been shown to influence crop productivity and farm income patterns across various agro-climatic regions(3). Such climatic fluctuations often compel farmers to adopt various coping and adaptation strategies to stabilize production and mitigate risk. As a result, farmers in semi-arid regions are increasingly implementing adaptive strategies to manage climatic risks and stabilize agricultural production.

2.2 Farmer Adaptation Strategies to Climate Change

In response to increasing climatic uncertainties, farmers employ a range of adaptation strategies to mitigate risks and sustain agricultural productivity. These strategies include crop diversification, adoption of improved crop varieties, irrigation management, and modifications in sowing patterns(3). Adaptation measures are essential for enhancing resilience and ensuring the sustainability of agricultural systems in the face of climate variability. Crop diversification is widely recognized as an effective risk-management strategy in agriculture. By cultivating multiple crops with different climatic sensitivities, farmers can mitigate the potential negative impacts of climatic shocks on overall farm income(4).

Diversified cropping systems improve resource utilization, reduce production risks, and enhance the stability of agricultural output. Studies have shown that diversification also contributes to improved soil health and biodiversity, thereby supporting long-term agricultural sustainability(5). In addition to diversification, technological innovations are pivotal in bolstering agricultural resilience. Climate-smart agricultural technologies, including drought-tolerant crop varieties, advanced irrigation systems, and soil moisture conservation practices, have been advocated to mitigate the vulnerability of agricultural systems(6). These technologies enhance water-use efficiency, stabilize crop yields, and improve farm productivity in climate-sensitive regions. The adoption of these technologies enhances the efficiency of resource utilization and strengthens farmers' ability to sustain productivity amidst uncertain climatic conditions.

2.3 Role of Institutional Support in Agricultural Adaptation

Institutional factors are pivotal in enabling farmers to adapt to climate change. Access to extension services, credit facilities, government programs, and farmer cooperatives significantly influences the adoption of climate-resilient agricultural practices(7). These institutional mechanisms facilitate farmers' acquisition of information regarding advanced technologies, climate forecasts, and sustainable farming practices. Research indicates that farmers with enhanced access to institutional support are more inclined to adopt adaptive agricultural strategies. Extension services, in particular, are instrumental in disseminating knowledge about climate-smart technologies and promoting sustainable farming practices(3).

Similarly, access to financial resources enables farmers to invest in improved technologies and infrastructure, thereby enhancing resilience to climatic stress. Furthermore, institutional support systems bolster farmers' adaptive capacity by facilitating knowledge sharing and providing access to agricultural inputs and resources. Such institutional interventions are especially crucial in developing regions where farmers encounter constraints related to limited resources and information(7). Farmers with strong institutional affiliations are more likely to adopt innovative agricultural practices and diversify their cropping systems.

2.4 Climate Impacts and Economic Vulnerability in Semi-Arid South India

Empirical research examining the intersection of climate and economics in the semi-arid regions of South India indicates significant yield and income reductions among farming households, attributable to rising temperatures and increased rainfall variability. Ricardian analyses consistently demonstrate negative income elasticities in relation to temperature. For instance, in Ramanathapuram, a 1% increase in maximum temperature during the Kharif season resulted in a 0.45% reduction in net farm income, accompanied by a 38% decline in yields due to rising temperatures and decreasing rainfall(7). Similarly, in Andhra Pradesh, a 1 °C increase was estimated to reduce rice net income by approximately ₹109 per hectare(8). Long-term projections for Tamil Nadu suggest potential declines of approximately 10% in rice yield and 9% in sorghum yield by the end of the century under mid-range scenarios(9).

Integrated modeling studies suggest that approximately 68% of fallow–chickpea households in semi-arid Andhra Pradesh are vulnerable under warmer climate scenarios, compared to 42% under wetter conditions(10). Field studies have documented a decline in demand for agricultural labor, groundwater-induced distress, and migration associated with recurring droughts and yield losses(11,12). Basin-level analyses in the Pennar and Godavari basins corroborate the increasing frequency of droughts and the consequent production losses(13,14).

District-level analyses identify Anantapur, Kurnool, Ramanathapuram, and Kolar as significant hotspots of climate sensitivity, particularly concerning crops such as rice, groundnut, and sorghum(10,15,16). Policy recommendations focus on enhancing water security through micro-irrigation, groundwater governance, and water reuse; promoting short-duration and heat/drought-tolerant crop varieties; and improving soil-moisture conservation through agroforestry and regenerative farming(15,17). Institutional reforms, such as expanded crop insurance, microfinance, and participatory extension, are advocated to enhance local adaptive capacity(18,19). Future research directions include linking downscaled climate projections with household economic models and conducting longitudinal evaluations of climate-smart interventions at scale(20,21).

Despite significant advancements in understanding the effects of climate variability on agriculture, several critical research gaps persist. Current studies frequently concentrate on either climatic trends or socioeconomic factors influencing adaptation in isolation, with limited integration of these elements within a comprehensive analytical framework. Notably, there is a paucity of empirical evidence regarding the combined effects of institutional access, crop diversification, and technological adoption on agricultural sustainability at the district level.

This study integrates climatic trend analysis with farm-level econometric analysis to provide district-level evidence on the determinants of agricultural resilience in the semi-arid regions of South India. Addressing these gaps requires integrated analytical approaches that combine downscaled climate projections with household-level economic data and longitudinal assessments of climate-smart interventions. This research contributes to the existing literature by examining the interaction between climate variability, institutional support, technological adoption, and agricultural sustainability in the Vellore district of Tamil Nadu.

Conceptual Framework:

The literature reviewed herein indicates that agricultural sustainability in semi-arid regions is influenced by the interplay between climatic variability and socioeconomic adaptation mechanisms. Climatic variability, characterized by increasing temperatures and unpredictable rainfall, heightens production risks and impacts agricultural decision-making processes. Nevertheless, farmers' responses to these climatic challenges are influenced by institutional and technological factors. Access to extension services, financial resources, and institutional support enhances farmers' capacity to adopt climate-smart technologies and diversify cropping systems. These adaptive strategies, in turn, affect the long-term sustainability of agricultural production by enhancing resource-use efficiency, stabilizing farm income, and reducing vulnerability to climatic shocks. Consequently, this study conceptualizes agricultural sustainability as an outcome of the interaction between climate variability, institutional access, technology adoption, and crop diversification at the farm level. By integrating climatic trend analysis with econometric examination of farm-level behavior, the framework facilitates a comprehensive assessment of how environmental and socioeconomic factors collectively shape agricultural resilience in semi-arid regions.

3. Materials and methods:

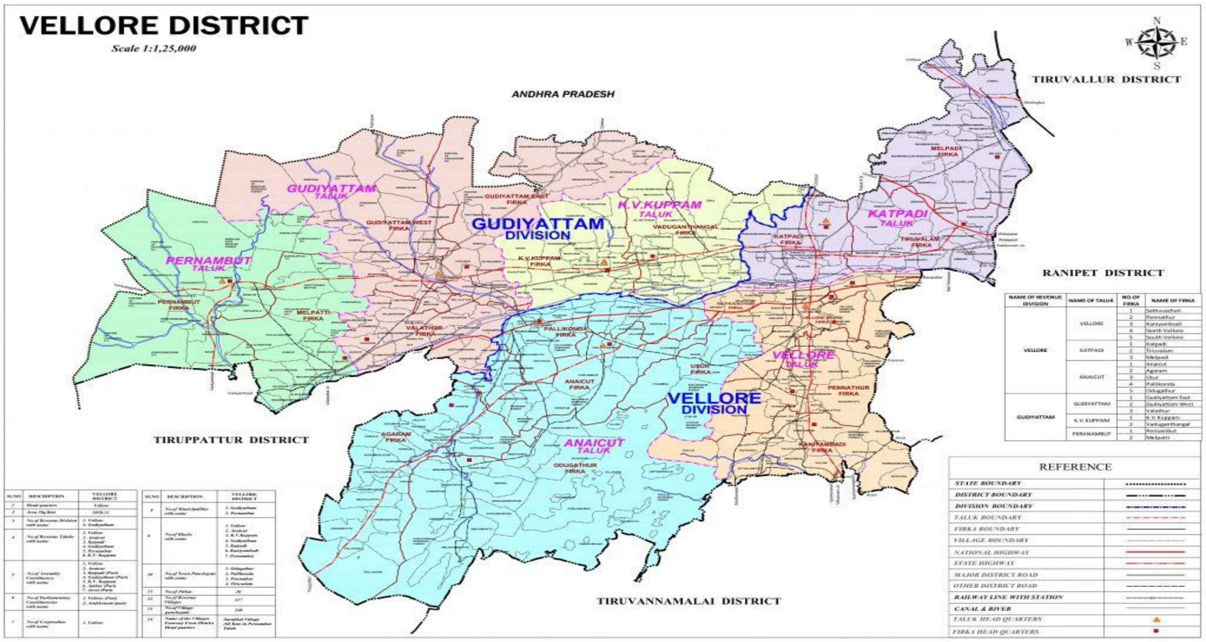
Study Area

The research was conducted in the Vellore district of Tamil Nadu, located in the northeastern region of the state, between 12°15′ and 13°15′ N latitudes and 78°20′ and 79°50′ E longitudes. This district is characterized by a semi-arid tropical climate, with an average annual rainfall of approximately 950 mm, sourced from both the Southwest (June–September) and Northeast (October–December) monsoons. The spatial and temporal distribution of rainfall in this area is highly erratic, leading to frequent droughts, crop failures, and fluctuations in agricultural income.

Vellore's agro-ecological landscape is predominantly defined by red loamy and lateritic soils, which possess moderate fertility and limited water retention capacity. Consequently, the region is particularly vulnerable to temperature increases and rainfall variability. The primary crops cultivated include paddy, sugarcane, groundnut, ragi, and millets, with paddy being the most prevalent due to its cultural and economic importance. However, due to water scarcity and high input costs, there is an increasing trend among farmers to adopt diversified and less water-intensive cropping systems(22).

In the aftermath of the district trifurcation in 2019, Vellore was partitioned into the districts of Vellore, Ranipet, and Tirupattur. For the purpose of analytical consistency, this study employs data corresponding to the pre-division boundaries of Vellore district to encompass its full agro-ecological and climatic diversity. The district functions as a microcosm of semi-arid South India, offering a representative framework to investigate the interplay between climatic and institutional factors in shaping agricultural resilience.

Figure 1 – Map of Vellore District



Source : Map of Vellore District (22)

Data Sources and Nature of Data

The study employs a mixed-methods approach, integrating secondary climatic data with primary household-level data.

(a) Climatic Data

Long-term climatic data were obtained from the India Meteorological Department (IMD) for the period 2001–2019. The dataset includes annual and seasonal rainfall (mm), mean maximum temperature (°C), and mean minimum temperature (°C). Derived indicators, such as the Rainfall Anomaly Index (RAI), Coefficient of Variation (CV), and temperature deviation index, were calculated to evaluate the intensity and variability of climatic trends. To ensure empirical robustness, separate series were constructed for the Southwest Monsoon (SWM) and Northeast Monsoon (NEM), reflecting the dual dependence of Tamil Nadu's agricultural cycle.

$$RAI_t = \frac{(X_t - \bar{X})}{\sigma_X}$$

where Xt is rainfall in year t, X¯ is the mean rainfall, and σX is the standard deviation over the study period. The Compound Annual Growth Rate (CAGR) was also calculated for rainfall and temperature to identify directional trends in climatic shifts.

(b) Agricultural Production Data

Secondary data concerning the area, production, and yield of major crops were sourced from the Department of Economics and Statistics (Government of Tamil Nadu) for the period 2001–2022. These data enabled the calculation of crop diversification indices, specifically the Herfindahl Index (HI) and Crop Diversification Index (CDI).

$$HI = \sum_{i=1}^{n} \left(\frac{A_i}{A_T} \right)^2, \quad CDI = 1 - HI$$

where Ai is the area under crop i, and AT is the total cropped area. A lower HI (and hence higher CDI) implies greater diversification. These indices were computed for both block-level and district-level data to capture spatial patterns of diversification.

(c) Primary Farm-Level Data

To enhance the climatic and secondary datasets, primary survey data were obtained from 200 farmers across 20 villages, encompassing all agro-ecological zones within the district. The villages were selected using stratified random sampling to ensure representation of both rainfed and irrigated systems, various crop types, and different farm size categories. Data were collected through a structured questionnaire administered during the period 2023-2024. The reliability of the multi-item indices was assessed using Cronbach's alpha, which surpassed the acceptable threshold of 0.70.

Analytical Framework

This study employed a comprehensive econometric and statistical framework to examine the complex interactions between climate and agriculture, incorporating trend analysis, diversification measurement, and regression modeling.

Climate Trend Analysis

Temporal variations in rainfall and temperature were evaluated using a simple linear trend model:

$$Y_t = \alpha + \beta t + \varepsilon_t$$

where Yt denotes rainfall or temperature in year t, α represents the intercept, and β indicates the rate of change. The significance of β was assessed using t-statistics to determine increasing or decreasing trends. Furthermore, the Mann–Kendall test was employed as a non-parametric method to validate the direction and significance of long-term climatic trends, ensuring robustness against non-normal distributions.

Crop Diversification Analysis

Crop diversification serves as a crucial adaptive strategy in semi-arid agricultural systems, enabling farmers to mitigate risks associated with multiple crops. To assess this strategy, two indices were employed: the Herfindahl Index (HI), which measures the concentration of land area dedicated to major crops, and the Crop Diversification Index (CDI), the inverse of HI, which reflects the extent of diversification.

Econometric Model for Determinants of Diversification

To identify the determinants of diversification, a multiple linear regression model was specified as follows:

$$CDI_i = \beta_0 + \beta_1 RainVar_i + \beta_2 TempVar_i + \beta_3 ExtServ_i + \beta_4 TechAdopt_i + \beta_5 FarmSize_i + \beta_6 Income_i + \beta_7 CreditAcc_i$$

Where:

CDIi : Crop Diversification Index for the ith farmer

RainVari : Rainfall variability (CV of annual rainfall)

TempVari : Temperature deviation from mean

ExtServi : Access to extension services (dummy variable, 1 = access, 0 = no access)

TechAdopti : Technology adoption index (based on PCA of adoption variables)

FarmSizei : Operational holding size (hectares)

Incomei : Annual farm income (INR)

CreditAcci : Access to formal credit (binary variable)

The model was estimated using Ordinary Least Squares (OLS), incorporating robust standard errors to mitigate heteroskedasticity. Multicollinearity was evaluated through the Variance Inflation Factor (VIF), and normality was confirmed via Jarque–Bera tests.

Sustainability Assessment

A Sustainability Composite Index (SCI) was formulated through the application of Principal Component Analysis (PCA), encompassing the economic, social, and environmental dimensions of resilience. The following indicators were incorporated:

Table 1. Sustainability Composite Index

Indicator	Type	Measurement
Resource use efficiency	Economic	Output-input ratio
Income stability	Economic	Coefficient of variation in income
Technology intensity	Technological	Number of climate-smart practices adopted
Institutional access	Social	Index combining access to credit, extension, and cooperatives
Climate perception	Cognitive	Likert scale on awareness and responsiveness

The initial two principal components, which account for the maximum variance, were extracted to formulate the composite sustainability score. Subsequently, farmers were categorized into low, medium, and high sustainability groups based on their SCI values.

4. Results and discussion:

Trends in Climate Variability

The climatic analysis of the Vellore district for the period 2001–2019 reveals significant inter-annual variability in rainfall and a statistically significant warming trend in temperature. While rainfall patterns do not demonstrate a consistent long-term decline, the observed variability during both the Southwest and Northeast monsoon seasons introduces considerable uncertainty into agricultural production systems. This variability complicates decisions related to sowing, irrigation planning, and input management, particularly in semi-arid regions where farming systems are highly sensitive to monsoon performance.

In contrast to rainfall patterns, temperature trends exhibit a clear and statistically significant increase in both mean maximum and minimum temperatures. Rising temperature regimes are likely to intensify evapotranspiration rates, accelerate crop phenological cycles, and increase irrigation demand. These climatic pressures may, therefore, exacerbate production risks in rainfed farming systems unless farmers implement adaptive management practices. Similar warming trends and associated yield vulnerabilities have been documented in several semi-arid regions of South India, reinforcing concerns regarding the long-term sustainability of climate-sensitive cropping systems.

Trend analysis utilizing the Mann–Kendall test and Sen's slope estimator indicates a slight decline in Southwest Monsoon rainfall, although this trend is statistically insignificant. Conversely, Northeast Monsoon rainfall exhibits a mild upward tendency, yet this increase is also not statistically significant. These findings suggest that rainfall patterns in the region are increasingly characterized by variability rather than a consistent directional trend. Such variability can have significant implications for agricultural planning, as unpredictable rainfall timing disrupts sowing decisions, irrigation scheduling, and input management. Temperature trends, however, demonstrate a clearer pattern. Both mean maximum and minimum temperatures show statistically significant increasing trends over the study period. Rising temperatures are likely to affect crop phenology, evapotranspiration rates, and soil moisture availability, thereby increasing the vulnerability of rainfed agricultural systems. Similar warming trends have been documented in other semi-arid regions of South India, where temperature increases have been associated with declining crop yields and increased irrigation demand.

Table 3. Climate Variability Trends

Climate Parameter	Mean Value (2001-2019)	Trend Direction	Significance
Annual Rainfall (mm)	950	Slight decline	Not significant
Southwest Monsoon Rainfall (mm)	520	Decline	$p > 0.1$
Northeast Monsoon Rainfall (mm)	430	Mild increases	$p > 0.1$
Mean Max Temperature (°C)	33.6	Increase	$p < 0.05$
Mean Min Temperature (°C)	23.8	Increase	$p < 0.05$

Vellore's climate is predominantly characterized by variability in rainfall, rather than a simple decline. Temperature trends indicate a warming pattern, which holds significant implications for the stages of crop growth and the stability of yields.

Determinants of Crop Diversification

The regression results presented in Table 4 reveal that crop diversification in the Vellore district is predominantly influenced by institutional and technological factors, rather than direct climatic variability. The Technology Adoption Index displays a positive and statistically significant coefficient ($p < 0.01$), indicating that farmers who embrace modern agricultural practices are more inclined to diversify their cropping systems. Technologies such as improved seed varieties, drip irrigation systems, and soil-moisture conservation techniques enhance production stability and mitigate risk, thereby encouraging farmers to experiment with multiple crops.

Access to extension services also exerts a significant positive influence on diversification behavior ($p < 0.05$). Farmers who maintain regular contact with extension agents benefit from enhanced access to agronomic knowledge, market information, and government support programs. This facilitates

informed decision-making and promotes the adoption of diversified cropping patterns. These findings align with previous studies conducted in semi-arid regions of South India, which underscore the critical role of institutional support systems in fostering adaptive agricultural strategies.

Climatic variables, including rainfall anomalies, do not exhibit statistically significant effects on diversification behavior. This suggests that farmers' diversification decisions are shaped less by short-term climatic fluctuations and more by long-term economic incentives and institutional support mechanisms. In this context, diversification appears to function as a strategic adaptation strategy rather than a purely reactive response to climatic shocks.

Table 4. Crop Diversification Determinants

Variable	Coefficient Sign	Statistical Significance	Economic Interpretation
Technology Adoption Index	Positive	$p < 0.01$	Major driver of diversification
Extension Contact (binary)	Positive	$p < 0.05$	Increases access to market and crop knowledge
Farm Size (acres)	Positive	Not significant	Larger farms can diversify more

Annual Income (₹)	Positive	Marginal	Income stability supports risk-taking
Credit Access	Positive	Weak	Limited institutional impact
Rainfall Anomaly (NEM z)	Insignificant	-	Limited short-term climate impact

From an economic perspective, the findings underscore that institutional and technological factors exert a more significant influence than climatic factors in elucidating on-farm diversification behavior. Diversification is predominantly affected by access to technology and extension support, rather than direct variability in rainfall.

Determinants of Technology Adoption

The results of the logistic regression analysis reveal that institutional and economic factors significantly influence the adoption of agricultural technologies among farmers in the Vellore district. Extension contact is identified as the most critical determinant, enhancing the likelihood of technology adoption by approximately 23 percent. This underscores the pivotal role of knowledge dissemination and advisory services in promoting the diffusion of climate-resilient technologies.

Household income also demonstrates a statistically significant positive impact on adoption decisions. Farmers with higher income levels have a greater financial capacity to invest in modern agricultural technologies, such as irrigation infrastructure, improved crop varieties, and precision farming tools. Conversely, rainfall variability does not significantly affect technology adoption behavior, suggesting that farmers adopt technologies as part of long-term productivity strategies rather than as immediate responses to climatic shocks.

These findings support the argument that adaptive capacity in agricultural systems is predominantly shaped by socioeconomic and institutional conditions rather than by climatic exposure alone.

Table 5. Technology Adoption Determinants

Variable	**Marginal Effect**	**Significance**	**Interpretation**
Extension Contact	+0.23	$p < 0.01$	Increases probability of adoption by 23%
Annual Income (₹)	+0.05	$p < 0.05$	Higher income supports adoption capacity
Farm Size	+0.02	Not significant	Minor influence on adoption
Rainfall Variability	-0.01	Not significant	No direct influence

Technology adoption is primarily influenced by institutional involvement and financial resources. Climate variability does not exert a direct effect, indicating a proactive adaptation approach rather than a reactive one

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Determinants of Agricultural Sustainability

The analysis of the Sustainability Composite Index delineates a distinct hierarchy of factors influencing agricultural sustainability in the Vellore district. The adoption of technology emerges as the most significant determinant of sustainability outcomes ($p < 0.001$), underscoring the pivotal role of modern agricultural practices in enhancing resource-use efficiency and ensuring productivity stability.

Institutional access, particularly through extension services and cooperatives, also significantly contributes to sustainability outcomes. These institutions furnish farmers with technical knowledge, financial assistance, and market access, thereby bolstering their capacity to respond to climatic uncertainties.

While crop diversification positively influences sustainability outcomes, its impact is relatively moderate compared to technological adoption. This suggests that diversification alone may not suffice to ensure long-term agricultural resilience unless complemented by technological innovation and institutional support systems.

Table 6. Sustainability Outcomes

Variable Technology	**Coefficient Sign**	**Significance**	**Interpretation**
Adoption	Positive	$p < 0.001$	Strong positive determinant of sustainability
Extension Access	Positive	$p < 0.01$	Institutional linkage enhances long-term outcomes
Farm Size	Positive	Not significant	Larger farms have modest advantage
Annual Income	Positive	$p < 0.05$	Higher income promotes resilience
Crop Diversification	Positive	$p < 0.05$	Moderate contribution to stability

Technological and institutional support have emerged as the primary drivers of sustainability. Diversification, in isolation, proves inadequate without comprehensive institutional strengthening.

Robustness checks:

To verify the robustness of the empirical results, a series of robustness checks were conducted:

1. As a measure of robustness, the Entropy Index was employed. The findings were consistent with those derived from the Herfindahl-based CDI.
2. The Sustainability Composite Index (SCI) was recalculated by systematically excluding each dimension—economic, technological, and institutional—individually. The rankings of the farmers remained consistent throughout this process.
3. Diagnostic Tests - The Variance Inflation Factor (VIF) values were found to be below 5, indicating the absence of multicollinearity. The Breusch–Pagan tests revealed no significant heteroskedasticity following the application of robust standard errors.

These checks confirm the reliability of the regression results.

Policy Implications

The empirical findings of this study hold significant implications for agricultural policy in semi-arid regions. The pronounced impact of institutional access and technology adoption on diversification and sustainability outcomes suggests that climate resilience cannot be achieved solely through climatic risk management. Instead, fortifying rural institutional systems emerges as a critical pathway for enhancing farmers' adaptive capacity.

Firstly, the expansion and modernization of agricultural extension systems should be prioritized in policy agendas. The strong positive correlation between extension contact and both diversification and technology adoption underscores the pivotal role of knowledge dissemination in enabling farmers to implement adaptive strategies. Strengthening field-level advisory services, farmer field schools, and digital agricultural extension platforms could substantially enhance the diffusion of climate-resilient practices.

Secondly, targeted financial support mechanisms are essential to promote the adoption of climate-smart technologies. Given that technology adoption is positively associated with household income, small and marginal farmers may encounter financial barriers when investing in irrigation systems, improved seed varieties, or precision farming technologies. Subsidized credit programs, climate-smart technology grants, and micro-irrigation incentives could therefore expedite technological diffusion.

Thirdly, water resource management remains central to adaptation in semi-arid agricultural systems. Investments in tank rehabilitation, groundwater governance, and micro-irrigation infrastructure can enhance water-use efficiency while reducing farmers' vulnerability to rainfall variability.

Finally, localized climate-risk management strategies should be integrated into district-level agricultural planning. Climate information services, crop insurance programs, and diversification incentives can assist farmers in anticipating climatic variability and stabilizing farm incomes.

Collectively, these findings underscore that resilience in semi-arid agriculture must be supported institutionally and technologically, rather than being solely climate-driven. While this analysis focuses on the Vellore district, the results remain relevant to other semi-arid districts in peninsular India with similar agro-ecological and institutional conditions. The findings emphasize that diversification alone cannot ensure resilience; it must be integrated within a supportive policy framework that provides access to technology, finance, and knowledge.

Given the significant influence of institutional access and technology adoption, targeted interventions such as Farmer Field Schools, climate-smart credit programs, cooperative-based input delivery, and digital advisory platforms can enhance adaptive capacity. Strengthening water governance through tank rehabilitation and micro-irrigation subsidies will further mitigate production risk for smallholders. These measures support a transition from reactive coping mechanisms to proactive, technology-driven climate resilience.

5. Discussion and limitations:

The results of the regression analysis demonstrate that education, access to irrigation, and experience in adaptation significantly and positively influence farmers' income levels in the Vellore district. These findings align with established economic theories concerning human capital and adaptive efficiency(23,24), indicating that farmers who are better informed and equipped are more likely to make profitable production and adaptation decisions under climate stress.

The positive elasticity of education ($\beta = 0.41$) suggests that each additional level of schooling increases farm income by approximately 0.41%, assuming other factors remain constant. This implies that literacy and formal training enhance decision-making capabilities, enabling farmers to better interpret weather forecasts, diversify crops, and access institutional support.

Similarly, irrigation access ($\beta = 0.28$) exerts a statistically significant positive effect, confirming that irrigation is a crucial component of adaptive resilience in semi-arid regions. Given the district's dependence on monsoonal rainfall and the increasing unpredictability of both southwest and northeast monsoon patterns, investments in micro-irrigation, tank rehabilitation, and water-saving practices appear economically justified. Conversely, farm size exhibits diminishing returns beyond a certain threshold, indicating that marginal and smallholders are not necessarily less efficient. This supports the "inverse farm size–productivity relationship" frequently observed in South Asian agriculture, where smaller farms tend to be more intensively managed(25). However, challenges such as rising input costs and market access barriers may constrain scalability for smallholders.

The absence of significance for variables such as credit access and climate perception in the current model may indicate institutional inefficiencies and information asymmetries within rural credit systems. Although farmers' subjective perceptions of climate—particularly in recognizing rainfall decline—are accurate, they do not directly translate into income variations unless accompanied by concrete adaptive investments. This underscores a disconnect between awareness and action, where economic constraints and transaction costs impede effective responses to climate variability.

Overall, the findings of this study underscore the significance of socioeconomic and institutional factors in influencing agricultural resilience in semi-arid regions. Although climate variability undoubtedly impacts agricultural systems, the results suggest that farmers' adaptive capacity is predominantly mediated through institutional access, technological innovation, and economic resources. The pronounced influence of extension services observed in this study is consistent with previous research that highlights the role of knowledge dissemination in fostering climate-resilient agricultural practices. Extension networks facilitate the transfer of agronomic information, provide access to government programs, and encourage the adoption of improved production techniques by farmers.

Similarly, the positive correlation between technology adoption and sustainability outcomes supports the expanding body of literature on climate-smart agriculture. Technologies such as micro-irrigation systems, drought-tolerant crop varieties, and precision nutrient management practices are widely recognized for their potential to enhance productivity while conserving natural resources. The limited direct influence of climatic variables on diversification and technology adoption suggests that farmers may rely more heavily on institutional signals and economic incentives when making strategic agricultural decisions. This finding reinforces the notion that climate impacts on agriculture are often mediated through socioeconomic structures rather than through direct environmental exposure.

6. Conclusion:

This study offers empirical insights into the determinants of agricultural resilience and economic sustainability amidst climate variability in the Vellore district of Tamil Nadu. By integrating long-term climatic indicators with farm-level socioeconomic data collected from 200 farmers across 20 villages, the research provides a comprehensive assessment of how environmental stress interacts with institutional and household-level factors to shape adaptive capacity within semi-arid agricultural systems.

The empirical findings reveal that socioeconomic and institutional factors exert a more substantial influence on farmers' resilience than climatic variability alone. Specifically, access to irrigation, educational attainment, extension services, and prior adaptation experience significantly enhance the capacity of farming households to stabilize agricultural income and manage climate-related risks. These results suggest that climate variability impacts agricultural outcomes primarily through indirect socioeconomic pathways rather than solely through direct environmental shocks. Farmers with robust institutional linkages and access to technological resources exhibit a greater ability to diversify cropping patterns, adopt improved agricultural practices, and maintain productivity under uncertain monsoon conditions.

From an economic standpoint, the results support the argument that climate adaptation should be conceptualized not merely as a defensive response to environmental risks but as a productive investment that enhances long-term agricultural sustainability. When supported by institutional credit systems, climate-smart technologies, and knowledge dissemination through extension services, adaptive strategies generate measurable welfare gains and reduce the vulnerability of smallholder farmers to rainfall variability and temperature fluctuations. These findings align with the broader literature emphasizing the importance of human capital, technological diffusion, and institutional support in strengthening climate resilience in developing-country agricultural systems.

The policy implications of this study are therefore substantial. Rather than focusing exclusively on short-term climate risk mitigation, adaptation policies should prioritize strengthening rural institutional frameworks that enable farmers to respond effectively to climatic uncertainty. Investments in irrigation infrastructure, farmer education and training programs, agricultural extension networks, and access to affordable credit can significantly enhance adaptive capacity at the household level. In the context of Vellore district, such interventions would help transform traditional coping mechanisms into proactive adaptation strategies capable of sustaining agricultural livelihoods under increasingly variable climatic conditions.

Furthermore, the study underscores the importance of integrating climate information systems, crop diversification strategies, and risk-management tools such as crop insurance into regional agricultural planning. By enabling farmers to anticipate climatic variability and make informed production decisions, these mechanisms can improve farm income stability while reducing long-term vulnerability within semi-arid agro-ecosystems.

While the present analysis provides statistically robust evidence on the socioeconomic drivers of adaptation and income resilience, certain limitations remain. The cross-sectional nature of the dataset restricts the ability to capture long-term dynamic interactions between climatic variables and agricultural outcomes. Future research could therefore benefit from incorporating panel datasets, spatial econometric approaches, and village-level climate indicators to examine the temporal and spatial dimensions of climate impacts more comprehensively. Such approaches would further clarify how climate variability, institutional capacity, and market access jointly influence the economic sustainability of smallholder agriculture in semi-arid regions.

Overall, the findings demonstrate that agricultural sustainability under climate variability is shaped not only by environmental conditions but also by the strength of socioeconomic institutions and technological adoption. By empirically demonstrating that the effects of climate on agricultural performance are mediated through institutional and technological channels, this study contributes to the growing body of literature on climate-resilient agriculture and provides policy-relevant insights for designing region-specific adaptation strategies in the semi-arid regions of South India.

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Data availability: The data used in this study are available from the corresponding author upon reasonable request.

Abbreviation:

SWAT - Soil and Water Assessment Tool

EPIC - Erosion Productivity Impact Calculator

PRECIS - Providing Regional Climates for Impact Studies

IMD - India Meteorological Department

RAI - Rainfall Anomaly Index

CV - Coefficient of Variation

SWM - Southwest Monsoon

NEM - Northeast Monsoon

HI - Herfindahl Index

CDI - Crop Diversification Index

SCI - Sustainability Composite Index

PCA – Principal Component Analysis

OLS - Ordinary Least Squares

VIF - Variance Inflation Factor

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