Annals of Agri-bio Research
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Article

Economic Viability of Climate Adaptation Strategies in Agriculture: Evidence from Vellore District, Tamil Nadu

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How To Cite: Dheekshidha M. B., & Nilavathy K. (2026). Economic Viability of Climate Adaptation Strategies in Agriculture: Evidence from Vellore District, Tamil Nadu. *Annals of Agri-bio Research*, *31*(1), 28–39. https://doi.org/10.53941/agrbio.2026.100003

Received: 15 May 2025
Revised: 30 October 2025
Accepted: 21 January 2026
Published: 7 April 2026

Abstract: This study assesses the economic feasibility of climate adaptation strategies at the farm level in Vellore district, Tamil Nadu. We integrate meteorological data from 2001 to 2019 with a 2023–2024 survey of 200 farming households across 20 villages to evaluate the adoption, costs, and returns of adaptation strategies. A Climate Change Adaptation Index (CCAI) is developed, and the factors influencing adoption are analysed using multinomial logistic regression. Economic outcomes are assessed through panel regressions (fixed and random effects) on income and yield, and benefit–cost ratios (BCR's) for key adaptation strategies are calculated. Our main findings include: (i) investments in water management and climate-resilient crop varieties lead to significant income increases; (ii) climate-resilient varieties have the highest benefit–cost ratio (≈2.2), while water management provides the greatest marginal income benefit; (iii) farm size and credit access are strong predictors of adoption, raising concerns about equity for smallholders. The study provides evidence for targeting subsidies toward smallholders to enhance equitable adaptation. We conclude with policy recommendations to lower adoption costs for resource-limited farmers and emphasize public investments that enhance the net social benefits of adaptation strategies.

Keywords: climate adaptation economics; rural livelihoods; climate resilience; agricultural policy; semi-arid agriculture; Vellore district

1. Introduction

The agricultural sector in the Vellore district, Tamil Nadu, faces escalating challenges associated with climate change, economic volatility, and food security. Vellore, situated in the northern part of Tamil Nadu, has historically demonstrated a diverse agricultural landscape characterized by varied cropping patterns and traditional farming practices that have sustained local communities for generations. The agriculture sector is a crucial element of Vellore's economy, sustaining the livelihoods of more than 60% of the district's population. The rising frequency and intensity of extreme weather events, altered precipitation patterns, and heightened temperatures have created unprecedented challenges for the district's agricultural communities.

Recent research indicates that Vellore's agricultural output has undergone significant variations over the past decade, with climatic unpredictability recognized as a primary factor leading to economic instability among farming households. These alterations have resulted in anticipated annual economic deficits for the district's agricultural sector. Farmers in Vellore recognize the climate change impacts, particularly with fluctuations in rainfall and rising temperatures (Samiappan et al. 2022). The district's predominantly rain-dependent agriculture makes it particularly vulnerable to climate-related challenges, impacting the local population that relies on agricultural activities for their livelihood.

Research gap and contribution: While previous research has documented farmers' perceptions and adaptation practices in South India, few studies have rigorously assessed the economics by simultaneously (a) quantifying adoption determinants, (b) estimating marginal income and yield impacts using panel econometrics, and (c) evaluating benefit–cost ratios at the farm level within a unified framework. This paper addresses that gap by estimating adoption equations to identify constraints, using fixed-effects models to isolate within-household income responses, and calculating farm-level benefit–cost ratios to compare strategies based on profitability and equity. The contribution shifts the focus from descriptive adaptation inventories to an economic ranking of strategies that informs cost-effective policy.

In response to these economic demands, farmers are adjusting cropping schedules and diversifying crop selections to align more effectively with changing rainfall patterns and temperature variations. This involves the adoption of drought-resistant crop varieties that mature rapidly (Ratakonda et al. 2024; Samiappan et al. 2022). Strategies such as drilling new bore wells, deepening existing wells, and implementing water-conserving irrigation techniques are being employed to address the challenges of water scarcity (Samiappan et al. 2022). Integrated farming systems that combine livestock and agricultural cultivation, alongside soil and water conservation techniques, significantly contribute to enhancing resilience against climate impacts (Kumar et al. 2023).

The exchange of resources and knowledge among farmers enhances their adaptability and increases resilience (Mujayin et al. 2024). A significant percentage (84%) of farmers identified alterations in rainfall patterns as a pivotal concern affecting their agricultural practices (Samiappan et al. 2022). Recent governmental initiatives and legislative measures designed to promote climate-resilient agriculture in Vellore have yielded promising results; nevertheless, substantial challenges persist in extending these efforts to support the most vulnerable farming communities.

This study examines the financial effects of environmental change on Vellore's agricultural sector and evaluates the cost-efficiency of different adaptation strategies. It seeks to align policy implementation with practical realities, providing insights into feasible adaptation strategies that account for both environmental and economic aspects of agricultural sustainability. There is an immediate necessity for governmental policies that advocate sustainable agricultural practices and ensure access to climate-resilient technologies (Kumar et al. 2023; Ratakonda et al. 2024). While these adaptation strategies are crucial for fostering resilience, obstacles, including limited access to knowledge and financial resources, may hinder their efficacy. Overcoming these obstacles is crucial for advancing sustainable agricultural methods in the Vellore district.

This framework analyzes the complex interaction between climate change effects and agricultural economics in the Vellore region, with particular emphasis on the adaptation strategies utilized by farmers. The project intends to quantify economic losses due to climate unpredictability, evaluate the financial consequences of adaptation strategies, and develop a cost-benefit analysis of various resilience alternatives. The analysis expands upon previous research on climate resilience in semi-arid regions, with a particular focus on the socio-economic conditions of Vellore's agricultural community. Comprehending such procedures is crucial for devising specific approaches that enhance farmers' adaptive capacity while ensuring economic viability. Note on administrative boundaries and recent data. Vellore district was officially bifurcated into Vellore, Ranipet, and Tirupattur districts in 2019. To maintain temporal consistency, long-term climatic data (2001–2019) are analysed using pre-division boundaries, while the 2023–2024 household survey reflects the current administrative structure.

2. Theoretical Framework

We integrate three theoretical frameworks to develop testable hypotheses on farmers' adaptation behaviour:

(1) Sustainable Livelihoods: Scoones (1998) and Ribot (2010) suggest that adaptation depends on the availability and interaction of various capital stocks, including natural, physical, human, financial, and social. The empirical implication is that factors such as landholding size, educational attainment, access to credit, and social networks are the significant indicators of adoption. These factors are incorporated as covariates in the multinomial logit adoption models. The relevance of the sustainable livelihood framework to Vellore's agricultural context lies in its recognition that adaptation strategies are deeply embedded within local

socio-economic conditions and institutional structures, which is crucial for understanding how farmers leverage different forms of capital to develop effective adaptive responses.

(2) Economic Theory of Adaptation: Barrett & Constas (2014) and Mendelsohn (2000) conceptualise adaptation as an optimisation process under uncertainty, where farmers invest when the expected present value of net benefits exceeds the associated costs. The empirical implication is that benefit–cost ratios and investment expenditures determine the intensity of adoption. This theoretical perspective is particularly pertinent within the framework of Vellore's agricultural landscape. Anticipatory adaptations refer to proactive measures implemented before significant climate impacts occur, aiming for desirable environmental changes. Differentiating these aspects is crucial for comprehending the temporal and strategic dimensions of agricultural practices amid climate uncertainty. Accordingly, we compute farm-level BCRs and incorporate implementation costs as a covariate and as a part of cost-benefit analyses.

(3) Resilience and Adaptive Capacity: Holling (1973), Folke et al. (2010) and Walker et al. (2003) emphasize system dynamics and potential nonlinearities, such as thresholds and path dependence. The empirical implication is that we examine heterogeneous effects across different farm sizes and conduct robustness checks for nonlinear income responses using interaction terms and subgroup regressions. This comprehensive theoretical framework underpins our methodology and analysis, ensuring that our study of agricultural adaptation in the Vellore district accurately reflects the intricate interactions among economic, environmental, and social factors that shape farmers' adaptive strategies and their outcomes.

Together, these frameworks ensure that each econometric specification has a clear theoretical foundation and that the analysis captures the multifaceted economic, environmental, and social dimensions influencing farmers' adaptation strategies and outcomes in the Vellore district.

3. Methodology

3.1. Study Area and Sample Selection

The study was conducted in the Vellore district, situated between the North latitudes (12°15′ and 13°15′) and East longitudes (78°20′ and 79°50′), Tamil Nadu, India ("About District" | Government of India, n.d.). The district encompasses an area of 6077 km^2, predominantly characterized by an agricultural landscape. It exhibits semi-arid conditions, with an average annual rainfall of approximately 971.1 mm, distributed as follows: 39.8 mm in Winter, 106.6 mm in Summer, 439.1 mm during the Southwest Monsoon, and 385.6 mm in the Northeast Monsoon ("Agriculture" | Government of India, n.d.). The geographical extent and administrative structure of the study area are illustrated in Figure 1.

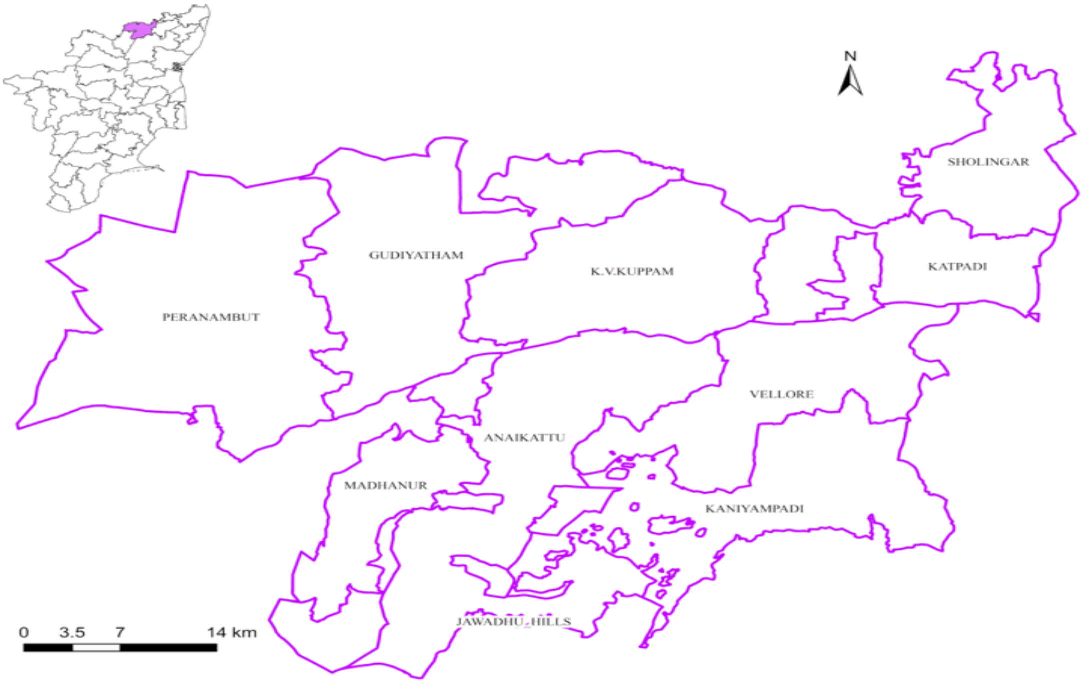

Figure 1. Illustration of the Vellore district post 2019. Source: "Vellore District" | Government of India (n.d.).

Rationale for Village selection: A multistage stratified random sampling method was utilized to select 20 villages based on (a) variations in agro-climatic conditions (tank-irrigated, borewell-dependent, and rain-fed areas), (b) diversity in cropping systems (paddy-dominant, mixed cropping, and horticulture), and (c) proximity to markets and extension services. Stratification variables were sourced from the District Statistical Handbook and local irrigation maps to ensure representation across different water-endowment strata. This explicit stratification enhances external validity for semi-arid subregions while facilitating internal comparisons across resource endowments. The final sample comprised 200 farming households, categorized by landholding size: Marginal (<1 hectare, n = 82), Small (1–2 hectares, n = 76), and Medium/Large (>2 hectares, n = 42). This sampling framework achieved a confidence level of 95% with a margin of error of ± 4.8%, following the sample size determination methods outlined by (Adam, 2020).

3.2. Data Collection and Variable Measurement

This study adopted a mixed-methods research design, incorporating longitudinal analysis of secondary data with cross-sectional primary data collection. The research methodology adheres to the systematic approach described by (Creswell and Creswell, 2017), incorporating both quantitative and qualitative components to ensure a comprehensive analysis of agricultural adaptation strategies in the Vellore district.

The secondary data collection spanning from 2001 to 2019, were obtained from the statistical department of the Vellore district (Department of Economics and Statistics District Office, Vellore district 2023) and validated with IMD district-level datasets. The data was collected based on the pre-division boundaries of Vellore district, prior to its trifurcation in 2019. This was essential for analyzing long-term climatic trends in the region. The dataset includes annual records of precipitation trends and temperature fluctuations. This temporal scope facilitates an in-depth trend analysis of climatic variations and their agricultural implications.

Primary data were collected during 2023–2024 through structured questionnaires distributed to 200 farming households across 20 villages, selected using a stratified multistage sampling design. The data correspond to the current administrative boundaries of Vellore district, ensuring relevance to the present socio-economic context. The questionnaire design followed the methodology of Kothari (2009) for agricultural surveys, utilizing both open-ended and closed-ended questions that include quantitative and qualitative dimensions of adaptation strategies.

Questionnaire structure and measurement: The survey instrument was divided into five modules:

(A) household socioeconomics (covering landholding, income, education);
(B) farm production and crop calendar (including area, yields, inputs by crop);
(C) adaptation practices (featuring binary and intensity measures for 18 listed options such as drip irrigation, crop diversification, conservation tillage, climate-resilient varieties);
(D) implementation costs and revenues (detailing itemized investments, maintenance, and observed yield changes); and
(E) institutional access (covering credit, extension contact, insurance enrolment).

Example items include: (i) "Have you adopted drip irrigation on any plot? (0/1). If yes, what was the total implementation cost in ₹?" (ii) "Please list top 3 crops and yield (kg/ha) in year t and year t − 1." The modules were numerically coded for econometric analysis.

The study's variables were designed following standard research methodologies (Elakhdar, n.d.). The effectiveness of agricultural adaptation, as the dependent variable, is assessed using various indicators, including crop yield stability, income variability, and the implementation rates of climate-resilient measures. Independent variables include climate factors such as rainfall, humidity, and extreme weather occurrences, alongside socioeconomic characteristics like farm size, income, and education, and institutional elements comprising access to finance, extension services, and market linkages.

The assessment of adaptation strategies employs a revised form of the Climate Change Adaptation Index developed by (Below et al. 2012), which evaluates the scope and efficacy of various adaptation measures. The index incorporates weighted scores for different adaptation strategies, ranging from 0 (no adaptation) to 1 (complete adaptation), determined by the level of implementation and perceived effectiveness.

3.3. Justification of Control Variables and Interaction Terms

Control variables were aligned with sustainable livelihoods mapping: landholding (natural/physical capital), household education and extension contact (human capital), access to credit and state/subsidy receipt (financial capital), and membership in farmer groups (social capital). Interaction terms included (i) farm size × adaptation to examine whether marginal returns differ by scale, and (ii) access to credit × cost to explore whether credit alleviates liquidity constraints that hinder profitable investments. These interactions are included because theory suggests heterogeneous marginal returns and adoption thresholds across capital endowments (Mendelsohn 2000; Barrett and Constas 2014).

3.4. Sampling Limitations and Biases

Sampling, administrative changes, and recall bias present certain limitations. Utilizing climatic data from before 2019 based on the pre-division boundary maintains long-term trend consistency but may cause discrepancies between climatic aggregates and the post-2019 administrative sample. This could lead to biased spatially-disaggregated inferences if climatic exposure varies within the pre-2019 boundary. To address this, we (i) present results aggregated to the common pre-2019 boundary for trend analysis and (ii) conduct robustness checks using post-2019 administrative strata and village-level weather data where available. Recall bias in reporting yield and input costs is minimized by cross-referencing with local mandi prices and extension records when possible.

3.5. Statistical Analysis and Model Specification

The econometric analysis utilizes E-views software to assess the relationship between climate variables, adaptation strategies, and agricultural outcomes. The panel data analysis adheres to the methodology defined by Gujarati, D. N. (2015), incorporating both fixed and random effects models to address time-invariant heterogeneity across farming households. The primary regression model is defined as:

$$Yit = \alpha + \beta1Xit + \beta2Zit + \beta3Wit + \mu i + \varepsilon it$$

where

Yit signifies the dependent variable for farmer i at time t;
Xit represents climate variables;
Zit represents adaptation strategies;
Wit includes variables of control;
μi incorporates unaccounted farmer-specific impacts;
while εit represents the error term.

The model estimation employs robust standard errors to address potential heteroscedasticity and serial correlation. The Hausman test is applied to determine the appropriate specification between fixed and random effects models. Furthermore, the analysis incorporates diagnostic assessments for multicollinearity, autocorrelation, and model specification, ensuring rigorous statistical inference.

Estimation and inference: all Coefficients are presented with robust standard errors and 95% confidence intervals. Diagnostic tests were conducted to ensure the robustness of results:

Autocorrelation: assessed using the Wooldridge tests for panel data. Which is corrected using village-cluster robust Standard errors.

(1) Hausman tests informed the decision between fixed- and random-effects models.
(2) Multicollinearity diagnostics (VIF < 10) suggest stable estimates.

We report both the adjusted R^2 and conditional R^2 (distinguishing between within and between components) to differentiate the variance explained within households from that across sections.

3.6. Linking Regression Estimates to Economic Viability

To connect econometric findings with economic interpretation, farm-level Benefit–Cost Ratios (BCRs) were calculated as:

$$BCR = \text{Change in Annual Net Benefits/Annualised Cost}$$

where Change in Annual Net Benefits represents the marginal change in annual net income derived from the fixed-effects regression estimates (adjusted for adoption intensity), and Annualised Cost denotes the discounted cost of implementing the adaptation strategy at a 10% discount rate over its expected lifespan.

Sensitivity analyses were performed using 6% and 12% discount rates to assess the robustness of BCR rankings to variations in the social discount rate. These computations ensure that the estimated economic viability reflects both the costs incurred and the realised benefits over time.

3.7. Validity and Reliability

The questionnaire was piloted with 30 households. The reliability of scales for multi-item constructs (such as adaptation intensity, institutional access index) was assessed using Cronbach's alpha, with all multi-item scales exceeding $\alpha = 0.70$. The pilot resulted in clarifications of wording for cost categories (capital, labour, fuel) and the addition of seasonal yield recall prompts to minimize measurement error.

3.8. Local yield Validation

Plot-level yields for paddy, groundnut, and sugarcane were gathered and verified against mandi and extension records. Regressions using these plot-level yields confirm the positive impacts of water-management and resilient-variety adoption, supporting a causal interpretation.

3.9. Overall Validity of Findings

The long-term integration of secondary data with primary survey data facilitates triangulation of findings, thereby enhancing the validity of conclusions. Furthermore, the econometric analysis employs multiple model specifications and sensitivity tests, confirming the robustness and stability of results across diverse analytical approaches.

Detailed definitions of variables and measurement indicators are provided in Appendix A (Table A1). Additional results on benefit–cost ratios and sensitivity analysis are presented in Appendix A (Tables A2 and A3).

4. Results

4.1. Climatic Trends and Agricultural Impact

An examination of meteorological data from the statistical department of Vellore district (2001–2019) reveals significant changes in climatic patterns. The mean annual temperature exhibits an upward trend, with maximum temperatures ranging from 37.2 °C in 2001–2002 to 42.8 °C in 2003, resulting in an average mean temperature of 39.8 °C. Meanwhile, minimum temperatures fluctuate between 12.6 °C and 27.8 °C. This trend indicates an increase in temperature extremes, which may adversely affect agricultural production and water supply.

Rainfall patterns demonstrate considerable inter-annual variability. Total annual precipitation ranged from 537.8 mm in 2018 to 1297.7 mm in 2005, showing significant deviations from average values in both directions. The coefficient of variation of rainfall has varied over time, with values of 31.9% during the 2001–2007 interval and 31.4% in the 2013–2019 interval, reflecting ongoing unpredictability. This variability poses challenges for farmers, particularly those dependent on rain-fed crops.

A more detailed analysis of monsoon patterns reveals that years with the most significant negative deviations from normal rainfall (2002, 2016, 2018) coincided with particularly weak Northeast monsoons. Additionally, notable temperature extremes rose dramatically to 27.8 °C and 27.0 °C, respectively, representing potential stress periods for traditional crops.

The increasing temperature trend and fluctuations in precipitation underscore the critical need for climate-resilient farming methods in Vellore. Implementing adaptation strategies, such as drought-resilient crop varieties, enhanced irrigation methods, and proactive alert mechanisms, is essential for sustaining agricultural productivity under climate change. The decadal variations in temperature and rainfall are summarised in Table 1.

Table 1. Decadal Climatic Variations in the Vellore District (2001–2019).

Period	Mean Temperature (°C)	Annual Rainfall (mm)	CV of Rainfall (%)
2001–2007	39.3	1004.6	31.9
2008–2012	40.1	898.0	13.5
2013–2019	39.7	795.2	31.4

4.2. Adaptation Strategy Analysis:

The climate trends in the Vellore district, characterized by rising temperature unpredictability and erratic monsoon patterns, have adversely affected agricultural productivity. Farmers have implemented adaptive strategies to mitigate risks and sustain production. This section examines the strategies and economic consequences utilized by the farmers and the primary variables influencing their adoption.

A multinomial logistic regression analysis examines the determinants influencing adaptation decisions. The findings reveal that farm size is a significant predictor of adaptation choices ($p < 0.01$), with larger farms demonstrating a higher likelihood of adopting capital-intensive strategies such as drip irrigation and enhanced water management practices. Table 2 details the adoption rates, implementation costs, annual returns, and benefit-cost ratios for the four primary adaptation strategies identified in the study.

Table 2. Contribution to Annual Precipitation Extremes.

Year	Southwest Monsoon (mm)	Northeast Monsoon (mm)	Total Annual Rainfall (mm)	Deviation from Normal (%)
2005	407.5	685.1	1297.7	+41.52
2016	354.49	139.48	585.08	−37.5
2018	318.1	181.5	537.8	−42.56

4.3. Statistical Analysis

A fixed-effects regression analysis was employed for assessing the impact of adaptation strategies on agricultural income. The model explained 72.4% of the variance in farm revenue (adjusted R^2 0.724), underscoring the substantial influence of adaptation techniques on agricultural productivity. The regression results presented in Table 3 indicate that all adaptation strategies significantly enhance farm income ($p < 0.0001$). Water management exhibits the most pronounced effect ($\beta = 0.621$, $p < 0.001$), highlighting its critical role in mitigating climate-induced water stress. The results of the fixed-effects regression model are reported in Table 4.

Table 3. Economic Impact and Adaptation Strategy.

Strategy	Adoption Rate (%)	Implementation Cost (₹/ha)	Annual Return (₹/ha)	Benefit-Cost Ratio
Crop Diversification	45.2	15,600	28,500	1.83
Water Management	38.7	42,000	65,800	1.57
Soil Conservation	28.3	22,500	31,200	1.39
Climate-Resilient Varieties	25.6	8200	18,400	2.24

Table 4. Fixed Effects Regression Results.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
Water Management	0.621	0.104	5.971	0.000
Crop Diversification	0.384	0.089	4.315	0.000
Soil Conservation	0.276	0.062	4.452	0.000
Climate-Resilient Varieties	0.312	0.076	4.105	0.000

4.4. Policy Implications and Recommendations

Socio-Economic Factors and Adaptation Strategies: Socioeconomic factors, such as education, financial accessibility, and awareness, significantly influence the role in shaping farmers' adaptation strategies to the impacts of climate change. Farmers possessing greater educational attainment are more inclined to implement soil and water management techniques and utilize crop insurance (Mohanraj et al., 2024). Similarly, access to credit facilitates the implementation of short-term measures, such as supplementary irrigation, and long-term strategies, including diversification(Ramasamy 2019). Farmers in Vellore are transitioning from traditional crops like paddy to shorter-duration and more profitable crops such as sorghum and maize. This shift is driven by the need to adapt to changing climatic conditions and maintain economic stability (Arumugam et al., 2014; Praveen et al. 2021). The effect of climate change has resulted in significant financial losses for farmers, with 70.00% reporting reduced productivity and 83.00% experiencing crop damage due to increased temperature and rainfall variability(Praveen et al. 2021; Ramasamy 2019). Therefore, socio-economic enablers must be integrated into broader institutional frameworks to ensure immediate and long-term resilience.

The Importance of Education and Awareness: Knowledge and understanding are crucial in enhancing farmers' adaptive capacity. Educational initiatives and awareness campaigns have been instrumental in promoting adaptation strategies. Informed farmers are more likely to adopt innovative approaches and leverage existing policy support(Mohanraj et al., 2024; Kumar et al. 2023). Examples include farmer field schools, training programs led by non-governmental organizations, and community-based information-sharing networks. These interventions facilitate the dissemination of information regarding available risk mitigation measures, government schemes, and technical innovations. Expanding crop insurance options and optimizing risk management strategies can provide financial protection to farmers facing climate-induced challenges(Mohanraj et al., 2024; Tyagi 2021). Hence, policy frameworks must prioritize farmer education alongside infrastructure and financial enhancements.

Institutional and Policy Support: Institutions and supportive policies are vital for facilitating adaptation at scale. Policies promoting climate-smart agricultural practices, offereing financial incentives can encourage farmers to adopt resilient practices. The integration of ICTs in agro-advisory services and the development of off-farm employment opportunities are crucial for sustaining livelihoods(Kumar et al. 2023). Crop insurance is a critical policy measure, providing financial protection to farmers experiencing crop losses due to climate-related adversities. Nevertheless, the scope and efficacy of these initiatives vary, as evidenced by the statistic that only 40.00% of farmers in certain regions benefit from such programs (Mohanraj et al., 2024; Tyagi 2021). Policies that promote environmentally conscious farming, including water and soil preservation methods and agroforestry, have shown positive outcomes. These practices enhance resilience, improve soil health, and optimize water efficiency (Khan et al. 2022; Kumar et al. 2023). The credit availability has significantly transformed the agricultural landscape, enabling farmers to implement adaptation strategies such as supplementary irrigation and the cultivation of drought-resistant crop varieties. However, institutional support and access to credit remain limited in many regions. Enhancing institutional support, including agricultural extension services and financial accessibility, is essential for facilitating the adoption of climate-resilient practices (Praveen et al. 2021; Ramasamy 2019). To address this, the government must strengthen the capabilities of local organizations, expand extension services, and ensure equitable access to financial resources.

Climate-Resilient Agriculture: This approach emphasizes practices that enhance productivity while simultaneously mitigating the risks associated with climate change. This includes the implementation of drought-resistant crop cultivars, water-efficient irrigation techniques, and agroforestry practices (Praveen et al. 2021; Rao et al. 2024). Water scarcity poses a significant challenge, with 92.50% of farmers reporting a decrease in irrigation intensity and 89.50% observing a reduction in water table levels (Ramasamy 2019). Consequently, this has led to reduced crop yields and increased vulnerability to drought conditions. Policies promoting efficient soil and water management practices have significantly impacted the adaptation tactics utilized by the farmers. Implementation of these measures has resulted in improved water retention and reduced soil degradation, thereby enhancing agricultural productivity (Mohanraj et al., 2024; Kumar et al. 2023). Crop diversification has emerged as an effective strategy, with farmers transitioning to crops such as peanuts, maize, and sorghum, which demonstrate greater resilience to climate variability. This shift has been facilitated by policies that improve market access and ensure price stability (Arumugam et al., 2014; Praveen et al. 2021). Consequently, it is imperative for policies to emphasize the advancement of climate-smart agricultural practices, including agroforestry and water-efficient irrigation, to enhance resilience and productivity (Khan et al. 2022; Kumar et al. 2023). Moreover, it is critical to prioritize educational initiatives and awareness campaigns to equip farmers with knowledge about climate-resilient practices and the policy support available to them (Mohanraj et al., 2024; Kumar et al. 2023).

5. Discussion

Separating descriptive and inferential results. Climatic-trend explains variability but do not suggest causation. Inferential results are derived from within-household regressions that determine the marginal economic returns to adaptation after accounting for shocks and fixed effects. This distinction clarifies the evidentiary status of each result.

Integration of Economic and Environmental Factors: The study's findings enhance the existing body of research on climate-resilient agriculture by emphasising the economic aspects of adaptation strategies. While prior research has often concentrated on either environmental resilience or broader socioeconomic issues, our integrated approach elucidates the critical interconnection between economic decision-making and environmental sustainability. The elevated benefit-cost ratios for all adaptation options challenge the notion that economic and environmental objectives are inherently incompatible in agricultural adaptation. Our results align with(Barrett and Constas 2014), who emphasized that adaptation is fundamentally an economic endeavour. Our research extends their approach by demonstrating that socioeconomic enablers—specifically education, access to credit, and institutional support—are pivotal mediating factors in the adoption of economically beneficial adaptation techniques. The significant impact of water management practices on income stability (β = 0.621) supports(Ramasamy 2019), asserting that water security is a fundamental component of agricultural resilience in semi-arid regions such as Vellore.

Differentiated Adaptation Capabilities: The notable association between farm size and adaptation strategies highlights equity issues in climate change adaptation processes. Smaller landholders, despite facing a higher relative risk from climatic variability, exhibit lower adoption rates for all adaptation methods. This finding corroborates(O'Brien et al. 2004)differentiation between anticipatory and reactive methods, indicating that resource-constrained farmers often resort to reactive measures, which yield suboptimal economic returns. Our data suggest that adaptation capabilities are unevenly distributed across the agricultural community, with 70.84% of farmers reporting reduced productivity and 23.50% experiencing crop loss due to climatic variability. This differential vulnerability necessitates targeted intervention strategies rather than universal solutions. The regression results indicate that substantial income improvements from adaptation strategies suggest that overcoming adoption barriers could significantly reduce economic disparities among agricultural households.

Contextual Policy Implications: The economic returns presented in this study strongly advocate for institutional investment in adaptation technology and information dissemination. The comprehensive theoretical approach employed here demonstrates that adaptation solutions should be evaluated for their technical effectiveness and economic feasibility within specific socioeconomic contexts. Policy interventions should focus on minimizing implementation costs for smaller farmers while enhancing information transfer systems. Our analysis corroborates the findings of(Kumar et al. 2023)Sustainable agricultural practices offer considerable economic benefits, yet require supportive institutional frameworks to overcome adoption barriers. The elevated benefit-cost ratios for climate-resilient varieties (2.24) and water management (1.57) indicate that these technologies represent sound economic investments for individual farmers and public policy initiatives. However, the realization of these benefits is contingent upon effectively addressing the socioeconomic factors that currently impede widespread adoption.

6. Conclusions

This study offers an extensive analysis of climate change adaptation tactics employed by farmers in the Vellore district and their economic implications. The findings reveal a significant annual temperature increase of 0.054 °C and stable rainfall variability (coefficient of variation remaining relatively consistent at approximately 31.9% to 31.4%) from 2001 to 2019, which impacts agricultural production. Farmers have adopted various adaptation strategies, with water management demonstrating the most substantial positive effect on farm income ($\beta = 0.621$, $p < 0.001$), followed by crop diversification ($\beta = 0.384$, $p < 0.001$), soil conservation ($\beta = 0.276$, $p < 0.001$), and climate-resilient varieties ($\beta = 0.312$, $p < 0.001$).

The economic analysis suggests that all four primary adaptation options yield favourable benefit-cost ratios, with climate-resilient varieties offering the highest return (2.24), although they require considerable initial knowledge and investment. The regression model explained 72.4% of the variance in income (adjusted $R^2 = 0.724$), suggesting that adaptation measures significantly enhance agricultural economic resilience to climate change.

Farm size emerged as a significant determinant influencing adaptation decisions ($p < 0.01$), with larger farms showing a greater inclination towards capital-intensive approaches. Additional analysis of monsoon patterns revealed that years with the highest rainfall deficits (2005, 2016, 2018) corresponded with particularly weak Northeast monsoons, suggesting targeted seasonal adaptation strategies may be specifically beneficial. Socioeconomic factors, particularly education and financial accessibility, significantly affect adaptation capacity and implementation rates. This study effectively employed an integrated theoretical framework to elucidate the complex interactions among climatic stressors, adaptation choices, and economic outcomes.

The analysis demonstrates that climate-resilient varieties and water-management investments provide the highest net benefits. Therefore, policy should (i) subsidize or offer low-interest credit for initial costs, (ii) enhance extension and information flows to reduce knowledge barriers, and (iii) expand collective water infrastructure to increase social returns. These measures maximize welfare gains by improving the marginal net benefits for liquidity-constrained farmers.

Author Contributions

B.D.: Conceptualization, methodology, data curation, formal analysis, investigation, writing—original draft preparation. K.N.: Supervision, validation, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request. The data are not publicly available due to privacy and confidentiality considerations of the survey respondents.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

Appendix A

Detailed definitions of variables and measurement indicators are provided in Appendix A (Table A1).

Table A1. Variable Definition and Measurement.

Variable	Definition	Unit	Expected Sign
Income (Y)	Annual agricultural income of the household	₹ per household per year	–
Crop Yield	Average yield across major crops (paddy, groundnut, sugarcane)	kg/ha	+
Rainfall Deviation Index (RDI)	Percentage deviation of annual rainfall from long-term normal	% deviation	±
Southwest Monsoon Rainfall	Rainfall received during southwest monsoon (June-Sept)	mm/year	+
Northeast Monsoon Rainfall	Rainfall received during northeast monsoon (Oct-Dec)	mm/year	+
Temperature (Max)	Annual average of maximum temperature	°C	–
Temperature (Min)	Annual average of minimum temperature	°C	–
Adaptation Index (CCAI)	Composite index of adaptation strategies (Below et al. 2012)	Scale 0–1	+
Water Management Practice	Adoption of irrigation or water-harvesting structure	Dummy: 1 = yes, 0 = no	+
Climate-Resilient Variety	Use of drought/flood-tolerant crop varieties	Dummy: 1 = yes, 0 = no	+
Crop Diversification	Number of different crops cultivated per season	Count	+

Table A1. *Cont.*

Variable	Definition	Unit	Expected Sign
Soil Conservation	Use of mulching, contour bunding, or green manure	Dummy: 1 = yes, 0 = no	+
Farm Size	Total operational landholding	Hectares	+
Education	Years of schooling of household head	Years	+
Access to Credit	Access to formal/informal credit sources	Dummy: 1 = yes, 0 = no	+
Extension Contact	Frequency of contact with agricultural extension officer	Number of visits/year	+
Membership in Farmer Group	Whether the household is a member of a farmer or SHG group	Dummy: 1 = yes, 0 = no	+
Implementation Cost	Total cost incurred for adaptation implementation	₹ per hectare	−
Household Size	Number of household members	Count	±
Farm Type	Type of farming: irrigated/rainfed	Categorical	+

All continuous variables were standardised (z-scores) for regression estimation. Expected signs are based on theoretical predictions from the Sustainable Livelihoods and Economic Adaptation Frameworks.

Table A2 represents the estimated Benefit-cost ratios (BCRs) for the major adaptation strategies identified in the study, summarizing the economic viability of each intervention at the household level.

Table A2. Benefit-Cost Ratio (BCR) of Major Adaptation Strategies.

Adaptation Strategy	Implementation Cost (₹/ha)	Annual Return (₹/ha)	Benefit-Cost Ratio
Crop Diversification	15,600	28,500	1.83
Water Management	42,000	65,800	1.57
Soil Conservation	22,500	31,200	1.39
Climate-Resilient Varieties	8200	18,400	2.24

Table A3 illustrates the sensitivity of Benefit-cost ratios to alternative discount rates (6%,10%,12%), confirming that the ranking of adaptation strategies remains robust across reasonable variations in the social discount rate.

Table A3. Sensitivity of Benefit-Cost Ratios to Discount Rate Changes.

Adaptation Strategy	BCR @ 6%	BCR @ 10% (Base)	BCR @ 12%
Crop Diversification	1.92	1.83	1.76
Water Management	1.64	1.57	1.50
Soil Conservation	1.45	1.39	1.33
Climate-Resilient Varieties	2.31	2.24	2.17

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