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Climate-Smart Agriculture and Agroforestry as Optimal Adaptation Strategies for Sustainable Agriculture Across Agro-Climatic Regions

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Abstract: We conducted a comparative evaluation of ten climate change adaptation strategies across five diverse agro-climatic regions to identify optimal practices for sustainable agriculture. The study employed a mixed-methods design integrating field observations, farmer surveys, and environmental monitoring across 300 farms, with statistical analyses including ANOVA, principal component analysis, and multiple regression. Our central hypothesis was that certain measures would outperform others in simultaneously enhancing productivity, environmental resilience, and economic viability. Climate-smart agriculture and agroforestry emerged as the most effective strategies. Climate-smart agriculture achieved a crop yield of 6.2 t ha^{-1}, a water use efficiency of 2.81 kg m^{-3}, and a resilience score of 92, while agroforestry delivered 6.0 t ha^{-1}, the highest soil organic carbon content at 2.15%, and a remarkable greenhouse gas reduction of 42%. Drip irrigation attained the highest water use efficiency at 3.12 kg m^{-3}. Rainfed agricultural systems experienced the greatest yield improvement, increasing by 53% from 3.4 to 5.2 t ha^{-1} with adaptation. Moreover, agroforestry provided the highest net income at 3190 USD ha^{-1} and a benefit-cost ratio of 3.26, whereas climate-smart agriculture showed the highest benefit-cost ratio of 3.27. Primary barriers to adoption were high initial investment (mean 4.56 on a 1–5 scale) and limited technical knowledge (mean 4.33). Projection modeling indicated that climate resilience could increase from 74 in 2025 to 94 by 2035, with average crop yields rising from 4.8 to 6.7 t ha^{-1}.

Keywords: Keywords: Climate-Smart Agriculture, Agroforestry, Sustainable Agriculture, Climate Change Adaptation, Agro-Climatic Regions..

Introduction

Climate change is posing many challenges for agricultural systems around the globe with rising temperature, precipitation and extreme weather events regularly occurring more frequently (Baruah et al., 2026). Food security is vulnerable to the impacts of climate change and a high priority in global security, particularly in developing countries where smallholder farming is the predominant means by which rural populations in these countries secure food (Tesfay 2020). The risks facing agricultural production are especially pronounced across a diversity of agro-climatic regions, ranging from rain fed and agricultural production systems in the semi-arid regions to agricultural humid tropical, temperature and coastal region (Arya & Hegde 2026). All these regions have unique environmental, economic and policy spaces that influence and act as a control on the effects of climate variability and effectiveness of any adaptation action (Gautam & Rao, 2008). Water scarcity and land degradation of semi-arid regions are severely limiting in use of land for agriculture and coastal agricultural lands are facing salinisation problems because of sea-level rise (TOBESKANIAN, 2026). Rain-fed systems are especially vulnerable in comparison to the rest of the world's agricultural systems, as they are directly affected by the rain, and with the increasing uncertainty of rain, many are at risk (Dani, 2026).

For this purpose, various changes have been suggested and practised in different scenarios including climate smart agriculture, conservation agriculture, agroforestry, drip irrigation, rain water harvesting, intercropping or using drought resistant cultivars of the crop (Khan et al., 2025). There are only a few studies that have examined the performance of these practices at specific localities, but few comparative studies that have comparatively examined the relative effectiveness of these practices over multiple agro-climatic zones at the same time (Koesmaryono et al., 2025; Tripathi et al., 2026). Current studies do not look into an entire region, nor do they consider as many metrics as are needed for supporting policy-making (Urama & Ozor, 2011). Poor integrated knowledge base prevents evidence based and comprehensible framework to assist farmer decision and governmental investments on a scale.

The present study was thus designed to fill this important research gap and a comparative assessment of ten climate change adaptation options here was carried out in five agro-climatic zones. We tested the plausibility of our central hypothesis that some adaptation strategies are more effective than others in improving at the same time three key dimensions of agricultural sustainability – the productivity of the crop, the environmental resilience, the economic sustainability. Another additional assumption was that relative efficacy might be different across locations, as a result of the spatial variation in the socioeconomic settings and base climatic conditions and soil types (Bhatt et al., 2019). We used a mixed method approach to research design to test these hypothesis and involved field observations, farmer surveys, crop productivity assessments and environmental monitoring on 300 farms. The purpose was to determine which adaptations are the most effective to maximise the synergy that emerges from these adaptations, and to minimise trade-offs between competing adaptation goals.

This study's primary contribution is the comprehensive and multi-dimensional evaluation of making adaptations in different settings of climate and economy. To date, previous studies mostly investigated individual practices or practices in only one region (Romanenko et al., 2007) but not several performance indicators at once in an integrated manner as we did. This ensures that strategies can be identified that enhance productivity, environmental and economic dimensions in a balanced way instead of prioritizing the enhancement of one dimension at the expense of the others. Further, adoption barriers to performance facets are compared, which helps gain insight about how best to design policy for the prioritised rain-fed and semi-arid systems, where the estimated benefits of adaptation are greater. The results are thus relevant to evidence-based agricultural policy making, planning for sustainable development, and climate-smart agriculture both regionally and globally.

It will be organized in the following way in the rest of the paper. Section 2 provides an overview of the current literature on climate change impacts on agriculture, and studies on different adaptive responses in various agroclimatic conditions. The methodological framework employed is described in Section 3, including site criteria, sampling procedures, data collection procedures and statistic techniques, that would be compared with the contribution of drains values.Section 3 outlines the methodological framework used: site selection, sampling, data collection and statistical techniques used to compare data, with contribution of drains values. Empirical results for all measured parameters are summarized and a comparison of the relative performance of the different adaptation strategies made at the end of section 4. This research is further explored in section 5 in relation to the agriculture practices and the implications for policy. Finally, the main contributions, limitations and research directions described in Section 6, summarizes the paper.

Literature Review

Linkage between climate change and agricultural productivity is also very well documented in various continent and agricultural production systems and there have been consistent negative impacts of the rise of temperature and other climate changes on yield and agricultural production and livelihoods in rural communities today (Malebajoa, 2010). These impacts have been characterized by various modelling approaches, including statistical regression models, which establish links between historical weather data and generate weather conditions for the past and future (El-Mahroug et al., 2025); and process-based crop simulation models, which incorporate physiological, soil and atmospheric processes (El-Mahroug et al., 2025). For instance, the model DSSAT (Decision Support System for Agrotechnology Transfer) is used extensively to simulate the nature and extent of response for wheat, maize and rice to various climate scenarios, and estimate the loss of crop production, and periods of crop vulnerability were identified, (Tripathi et al., 2026). However, such modeling applications have been relatively run in just one site or local scale, and thus had limited ability to carry out a comparative evaluation between different agro-climatic regions.

Individual modes of adaptation were the focus of research literatures studies. The use of permanent soil cover, crop rotation and minimal soil disturbance under conservation agriculture have been shown to boost soil organic carbon (SOC) (R. Jat et al., 2014), while using drip irrigation has been demonstrated to be very effective for improving water retention in semi-arid sub-Saharan Africa and South Asia, with trials in India showing 40-60% increase in water use efficiency under drip irrigation compared to other irrigation technologies and methods, including flood irrigation (Venot et al., 2017). Featured are agroforestry systems; in addition to the other advantages, agroforestry systems have been shown to have the potential to improve biodiversity, carbon sequestration and microclimatic regulation (Jose, 2009). Drought stress is found to have a higher moisture content and a lower temperature under the agroforestry plots compared to monoculture fields in west Africa and in south east Asia during drought stressors/years (Bayala et al., 2014).

Nevertheless, the current literature has a number of methodological shortcomings which are overcome in the present study. For one, most investigations concentrate on only a few practices in a small area and only identify those that are best in diverse contexts (Muchuru & Nhamo, 2019). Second, outcome measurement is often sector specific (for the agrifood sector, typically focusing on yield or profitability), and does not involve other indicators of environment sustainability that are also relevant (adaptation to climate change in the agrifood sector, barriers and opportunities, a systematic review, n.d.-a). Thirdly, Qualitative studies on adoption barriers not only do not have quantitative data to be considered alongside performance data for policy making purposes, but they have been discussed superficially to the degree that they are not very helpful (Chalchisa & Sani, 2016). Finally, studies on the temporal dimension of the effectiveness of adaptations has not been explored extensively with very few studies carrying out simulations of the relative success of different adaptation interventions under varying future climatic scenarios (Baruah et al., 2026).

The main aim of the present study is to fill these gaps for future research by designing a framework for the systematic comparative evaluation of the ten water-shooting techniques and application methodologies across the five agro-climatic regions on a consistent basis, based on a common set of multi-dimensional water-shooting performance indicators. Unlike the previous work that has focused on environmental, economic and productivity indicators, in our research principal component analysis and multiple regression are applied in order to identify how the aspects of the niau system can be addressed in an integrated way to achieve the highest value for the three dimensions of environment, economy and productivity. In addition, we have standardized them across a standardized scale, and employed projection modeling to the year 2035, both of which offer a new outlook which is not so widely represented in the literature. In addition, by following this methodological improvement, we are able to offer more sustainable adaptation recommendations in agriculture with higher level of robustness, generalization and practiceability than previous fragmented studies.

Methods

Comparative mixed methods research design was used in this study to compare the efficacy of climate change adaptation strategies for sustainable agriculture in different agro-climatic regionalization. The method collects data from various sources in the field such as observation, farmer survey, crop productivity assessment, environmental monitoring and statistical analysis and compares adaptations under different climatic conditions (A & Aboobaker, 2026).

Study Area and Sampling Design

To see the effect of the above, the investigation was carried out over five representative agricultural zones having different climatic characteristics, namely, a semi-arid region, a humid tropical region, a temperate region, a coastal agricultural region and a rain fed agricultural region as per Baruah et al., (2026). The choice of these zones was to reflect the entire range of climatic variations – from water deficient to water surplus and from inland regions to coastal regions subject to salinity processes – to which the agricultural system is exposed and under which system is currently functioning. (TOBESKANIAN, 2026).

The number of farms in each region that were studied was determined by stratified random sampling to create a total of 60 farms sampled from each of the five regions for a total sample of 300 study farms. Beyond ensuring representativeness within each agro-climatic zone, the stratification carried out was based on the size of the farms (small, medium and large), and on the dominant crops that were involved (to ensure representativeness within each type of stratification). The sampling method was designed to eliminate part of the sampling bias and to allow for a representation of the diversity in farming method adopted by the farmers in each region sampled.

Adaptation Strategies Assessed

Climate-smart agriculture, conservation agriculture, agroforestry, water harvesting, drip irrigation, organic agriculture, precision agriculture, integrated nutrient management, drought-tolerant crop varieties and crop diversification are 10 systemically assessed strategies to adjust climate change. All strategies were used to a_subset of farms in each region and conventional farming systems to a baseline control. Strategies to be implemented on farms were chosen because the farmers were already using this method, or primarily establishing it in experimental plots at the farms so that there could be sufficient replication for statistical analysis.

Data Collection Protocols

Primary data collected by using various complementary methods. The data specific to socio-economic factor, adoption and perceived barriers to the achievement were gathered through the administration of farmer questionnaires. In each of the regions, a focus group discussion was organised to interpret the quantitative findings and, to get an insight into the limitation of the community. The condition of the crop and management practices were monitored during the growing seasons. From the observation, soil samples were collected at the beginning and at the end of each vegetation period to investigate the changes of soil organic carbon. Standard area based crop yield sampling protocols were used to obtain harvest yield. Flow meters were used on the irrigation systems to monitor water use and in rainfed areas soil moisture sensors were used.

Secondary data includes data from the meteorological department for meteorology, agricultural department data report, FAO data bases, climate data from the IPCC, remote sensing images and published scientific literature. These secondary information sources provided background spatial information for primary observations, historical trends and regional background information.

Measured Parameters and Analytical Framework

Eight indicators, which are relevant from a sustainable and effective adaptation perspective in agriculture, were measured (see Table 1 for parameters). Three of the four measures of crop yield, water use efficiency, and farm income were measured in tonne per hectare (t ha-1); water use efficiency was also calculated as kg per m3 of water used (kg m-3); the third, in addition to being measured in tonnes per hectare (t ha-1), was expressed as US dollars per hectare (USD ha-1); and the fourth measure, the climate resilience score, was presented on a scale of 0 to 100. The measures of biodiversity and greenhouse gases were expressed as unitless and in tonnes of CO2 equivalents per hectare (t CO2-eq ha-1), respectively.

Table 1. Measured parameters and their units for evaluating adaptation strategy performance.

Parameter	Unit
Crop Yield	t ha^{-1}
Water Use Efficiency	kg m^{-3}
Soil Organic Carbon	%
Farm Income	USD ha^{-1}
Climate Resilience Score	0–100
Greenhouse Gas Emissions	t CO_2-eq ha^{-1}
Biodiversity Index	Score
Adaptation Cost	USD ha^{-1}

The comparative analytical framework was broken down into seven steps. The climate as it existed in first phase was analysed using past meteorological data to better understand the climatic trends at the regional level as far as temperature, precipitation and drought events were concerned (Bhatt et al., 2019). Second, adaptations strategies were selected for the farms, and allocated stratified. Thirdly, the monitoring was done in the farms throughout the study period at three time points – planting stage, mid-season and harvest stage. Fourth, crops productivity was measured in terms of yield and water use efficiency. Fifth, changes in soil organic carbon, GHGs and biodiversity indices were assessed by environmental impact assessment. Sixthly, the economic cost benefit analysis was carried out for farm income without considering the cost of adaptation and benefit cost ratios. The seventh approach was comparative statistical assessment which was used to come to a synthesis of all metrics and the development of optimal strategies.

Statistical Analysis

The data collected was processed and analysed using descriptive statistics which describes the central tendencies and variations on region and strategy. One-way analysis of variance (ANOVA) was used to determine if any overall differences between the performance measures of the various adaptation strategies existed; where significant differences were found, the Tukey's post hock test was used for group pair-wise comparisons (Panteleev et al., 2024). To eliminate the high inter-dependence of parameters measured and identify the covariance structure among different parameters to evaluate the performance, a Principal component analysis (PCA) has been done for 8 parameters. To quantify the strength/direction of linear relationships between pairs of measured parameters, Pearson correlation analysis was used. Multiple regression analysis were performed to model the crop yield and the crop scores of resilience on the basis of adaptation strategy, region and interaction terms. The level was considered to be statistically significant for all tests.

There were 300 study farms being measured with all of them involved in both all use and all statistical analysis, with groups of study farms (regions) as independent variables and with the eight parameters as dependent variables. Using multivariate and parametric methodology enabled the hypotheses to be tested and patterns to be explored in the multidimensional data.

Results

Significant differences were found across the agro-climatic regions for the ten adaptation strategies and climate-smart agriculture and agroforestry demonstrated highest performance for most aspects of sustainability. These results are further analyzed in the following sections as a series of seven parts: Overall performance of each one of the above seven strategies, Productivity slopes in each region of the above seven strategies, Soil health slopes in each strategy of the above seven strategies, Economic return to each strategy of the above seven strategies, Adoption constraints and Inter variables correlations of the above seven strategies with a prediction of what is likely to come in the future.

4.1 Comparative Performance of Adaptation Strategies

The winners of the competition were climate-smart agriculture and agroforestry, based on an exhaustive and detailed evaluation on the basis of the four pillars—crop productivity, water use efficiency, capacity to be resilient, and greenhouse gas mitigation. This is a resounding endorsement of the main hypothesis that there are options available that could contribute to enhancing several aspects of the sustainability of agriculture presented in table 1.

Table 1. Comparative performance of climate adaptation strategies across five agro-climatic regions.

Adaptation Strategy	Crop Yield (t ha^{-1})	Water Use Efficiency (kg m^{-3})	Resilience Score (0–100)	GHG Reduction (%)
Climate-smart Agriculture	6.2	2.81	92	38
Conservation Agriculture	5.8	2.64	87	34
Agroforestry	6.0	2.72	90	42
Drip Irrigation	5.7	3.12	85	29

Adaptation Strategy	Crop Yield (t ha⁻¹)	Water Use Efficiency (kg m⁻³)	Resilience Score (0–100)	GHG Reduction (%)
Crop Diversification	5.4	2.43	81	24

The best performance was achieved by climate-smart agriculture which yielded 6.2 t ha⁻¹, achieved a resilience score of 92 and a greenhouse gas reduction of 38%. It brings together various complementary practices, notably better water use, cultivating higher-yield plants and improved disease management which mitigate the probability of loss of production in the wake of climatic shocks (Climate-Smart Agriculture in South Asia, n.d.). A resilience score of >92 – farms adopting this system were able to produce more than 90% even in periods of heat stress and rainfall deficit – was improved than any other system except agroforestry.

The score was 6.0 t ha⁻¹ for agroforestry in terms of yield while it was 90 for agroforestry in terms of resilience and 42 % in terms of greenhouse gas reduction as compared to all the other strategies. The important reduction in emission is through carbon sequestration caused by woody perennials in an agristippled system forming biomass and soil organic matter from the atmosphere through CO_2 sequestration, and this is a phenomenon that is very well established. (Carbon Sequestration Potential of Agroforestry Systems in the Tropics, 2007?). The plots above, however, had a higher resilience score, because the three beneficial effects mentioned were found in agroforestry plots: improvement of microclimate regulation, maintenance of soil moisture and diversification of income.

Among the irrigation water-use categories the highest water-use efficiency was obtained with drip irrigation (3.12 kg m-3), and was better than all other irrigation strategies in this water-use category. The results corroborated those of previous studies which reported drip irrigation can save 30–50% of water use compared to traditional irrigation systems and still maintain or even enhance crop yields (Al-Ghobari & Dewidar, 2018). Drip irrigation received a low score for resilience of 85, and a rating of 29 for greenhouse gas reduction and was an outlier with regards to water saving. The differences highlight that success for strategies which optimise one dimension can result in less holistic outcomes for the whole range of sustainability indicators.

The yield of the conservation agriculture was 5.8 t ha-1 and was 2.64 kg m-3 water use efficiency with resilience score of 87 and GHG reduction of 34%. Of the five strategies outlined, the least effective in terms of yield (5.4 t ha⁻¹), lowest GHG reduction (24%) and highest risk spreading and dietary diversity benefits were found to be policy diversification. The findings highlight the need for trade-off based on diversification benefit and productivity improvement with respect to more intensive system.

Using Principal component analysis, these patterns were confirmed in terms of a composite component load, a majority of which loaded high on the increased yield, the all-reaching agroforestry and the climate-smart agriculture measures most of which comprised climate-smart agriculture and agroforestry that loaded high on resilience and emission reductions. They affect more than soil health because they are multivariate, considering multiple soil-water, soil-biological and other dimensions, which is why they are more productive than treatments that act on a single dimension such as drip irrigation or only crop diversification (Integrated Farming Systems for Climate Change Adaptation and Mitigation in the Indo-Gangetic Plains, n.d.). Therefore, the current comparative evidence here indicates the importance of pursuing these two adaptation action pathways in planning for adaptation scenarios in various agro-climatic zones.

4.2 Regional Crop Productivity

The insights on the productivity of the various agro-climatic regions and its cultivation intensity and intensity of cultivation through the various adaptations indicated that generally it did lead to yield gains when the productivity effect was calculated in relation to the conventional cultivation situation. This variation demonstrates the important point that adaptation designs are not necessarily the same in every environment (Baruah et al., 2026), rather they need to be designed and implemented according to the specific environment and need.

As can be seen in Table 1, the highest relative yield increases were obtained for the rainfed situation, with the adaptation strategies resulting in a yield increase to 5.2 t ha^{-1}, while conventional farming resulted in an increase to 3.4 t ha^{-1}. This major benefit may be due to the high responsiveness of the rain fed systems to climatic variations as there is no any any backstop irrigation supply to mitigate it in the agriculture system (Gautam & Rao, 2008). RWH, adaptation of drought resistant crops and conservation tillage are direct measures that support water scarcity problem and offer a wide range of latent productivity potential in these systems. There is a particular emphasis on the roll out of adaptation gains per dollar invested in the rain fed zone: adaptation benefits and risks are greatest in this area, making policy action and funding priority.

After the adaptation, the yield was increased by 47% due to the conventional management in the semi-arid areas which increased from 3.6t ha-^{1} to 5.3t ha-^{1}. Water shortage is a recurring problem in the semi-arid region with often wide inter-annual and intra-annual variation in rainfall causing the region to be especially sensitive to water-saving technologies and stress-tolerant crop varieties (TOBESKANIAN, 2026). Empirical evidence was found to be positive as the targeted adaptation measures resulted in very significant increase of 47% in the observed areas of difficulty.

Table 1. Crop yield under different agro-climatic regions comparing conventional farming and adaptation strategies performance.

Region	Conventional Farming (t ha^{-1})	Adaptation Strategies (t ha^{-1})	Yield Increase (%)
Semi-arid	3.6	5.3	47
Humid Tropical	4.7	6.4	36
Temperate	5.0	6.6	32
Coastal	4.3	5.9	37
Rainfed	3.4	5.2	53

The coastal agricultural condition observed the gain of yield by 37 % (from 4.3 to 5.9 t ha-1) while the humid tropical condition observed the new gain of yield by 36 % (from 4.7 to 6.4 t ha-1). Salinity stress in coastal zones and pest in humid zones were the strategies that benefited these areas but because of the relatively higher productivity in these areas than in other stressed areas, the enhancement they achieved was less than proportionate (Bhatt et al., 2019). Increases in the relative terms were least at 32% in the temperate region (from 5.0 to 6.6 t ha^{-1}), probably due to the relatively favorable climatic conditions and management practices of these areas, which have less scope for adaptation-related change than the other areas.

Specifically, the absolute yield in humid tropics and temperate regions are larger after adaptation (6.4 and 6.6 t ha^{-1} respectively) showing that productivity potential still plays a significant role for absolute yield after adaptation, irrespective of regions. However, the big differences between the relative productivity gains from rainfed systems and semi-arid systems show that adaptation options can dramatically narrow the productivity gap between the more favorable and more stressful rainfed and semi-arid systems at national and global scales, leading to increased equity and resilience of the agricultural system (Dani, 2026). The results further underscore that water productivity gains achieved by adaption investments can be valuable and extend the food security benefits of water constrained locations.

4.3 Soil Health Improvement

In addition to the gains in crop productivity, implementing climate adaptation measures delivered large increase in soil health measures in all five agro climatic regions (with significant differences between the potential to each of these measures of soil health scores). Above mentioned soil health assumptions constitute an extremely essential soil health metrics that impact its water filtering model, nutrient transformation and soil's organic connection with crop productivity (Hamidov et al., 2018).

Among all strategies assessed, agroforestry had the best soil organic carbon content of 2.15%, and the highest score in the biodiversity index as 93 (as presented in Table 2) and thus showed the most effective results. All of these benefits result from the constant influx of tree litter (organic matter) and the development of extensive root networks that enhance soil structure and provide a wide range of micro-habitats that facilitate a wide range of soil organisms (Lori et al., 2022). Agroforestry provides the opportunity to plant woody perennials with deep rooting which will contribute to CO_2 storage at greater depths than with annual cropping systems; producing higher overall C sequestration potential and better soil long-term stability (Gama-Rodrigues et al., 2011).

Table 2. Soil quality indicators across different climate adaptation strategies.

Adaptation Strategy	Soil Organic Carbon (%)	Biodiversity Index
Climate-smart Agriculture	1.84	82
Conservation Agriculture	1.91	86
Agroforestry	2.15	93
Drip Irrigation	1.63	74
Crop Diversification	1.79	81

The second best soil OC was recorded in conservation agriculture with 1.91%, while highest biodiversity index was recorded in it which amounted to 86. Planting crops with perennal soil cover using crop residues or cover crops, or opting for decreased tillage frequency and intensity can slow loss of soil carbon as oxidation is reduced and increase soil carbon in surface layers (n.d. Conservation Agriculture Effects on Soil Organic Carbon and Nitrogen in the Indo-Gangetic Plains). A biodiversity figure of 86 indicates that rotations of diverse crops, and less soil disturbance, have positive effects on soil fauna, such as earthworms, arthropods and microbial populations which constitute a large part of the nutrient cycling processes (Kassam et al., 2009).

The Soil organic Carbon (SOC) varied from 1.84% in Climate intelligent Agriculture (CSA) whereas the BDI was recorded at the value of 82. It involves a group of practices designed to enhance soil health, such as agro-cycling of nutrients and crop rotation, but also has relatively low levels of soil carbon compared to agroforestry and conservation agriculture and introducing perennials may be an important variable to boost soil carbon in agricultural soils (H. Jat et al., 2020).

The irrigation method that shows the lowest value of SOC concentration is drip irrigation (1.63%) and for biodiversity index is the lowest (74). Such a pattern could be attributed to the higher production resulting from the drip system, where nutrient applications were higher and more often used cultivation cycles (dripped more often), which can impact the rate of organic matter decomposition (Ji et al., 2026).

Many drip-irrigated systems also do poorly in terms of perennial vegetation and contribution of organic matter from a cover crop, further reducing soil carbon builds and biological diversity.

Crop diversification had intermediate soil health indicators, soil organic C (1.79%) and biodiversity index (81). Although the biomass, biodiversity and species diversity above and below the ground are greater than in "traditional agriculture", there are still some impacts that are smaller than the soil carbon found in agroforestry systems (Crop Diversification Effects on Soil Biodiversity and Ecosystem Services in Agricultural Landscapes, n.d.). Overall the results confirm, that agroforestry and conservation agriculture are best options in restoring and maintaining soil health in agricultural landscapes adapting to climate change.

4.4 Economic Performance

Economic viability is crucial for the farmers' capacity to be able to carry out these cost-saving measures such as climate adaptation and scale-up the policy uptake. The cost benefit analysis conducted in the present study indicated that financial advantage during implementation of various recovery plans differed significantly, the financial benefit of climate smart agriculture and/or agroforestry is fetched by huge investment as exhibited in the table below.

Table 1. Cost-benefit analysis of selected climate adaptation strategies across five agro-climatic regions.

Strategy	Adaptation Cost (USD ha^{-1})	Net Income (USD ha^{-1})	Benefit-Cost Ratio
Climate-smart Agriculture	820	2680	3.27
Conservation Agriculture	710	2310	3.25
Agroforestry	980	3190	3.26
Drip Irrigation	890	2560	2.88
Crop Diversification	620	2010	3.24

Among all assessed strategies climate-smart agriculture had the best benefit-cost ratio (3.27) and positive net income (2680 USD ha^{-1}) at an implementation cost of 820 USD ha^{-1}. The main reason this is a favorable economic outcome is the use of a number of complementary practices that improve water use, reduce inputs, and introduce the ability for crops to withstand stress, all at once, through improvements in water management, nutrient application, and introducing stress-tolerant varieties (Climate-Smart Agriculture in South Asia, n.d.). The relatively moderate investments, combined with the high gains from more favourable yields and reduced inputs give a very good return on investment and make climate-smart agriculture an economically attractive option to farmers across agro-climatic zones.

Although agroforestry has the highest adaptation cost (980 USD ha-1), the highest absolute profit (3190 USD ha-1) was achieved with this strategy. The improved BCR of 3.26 for climate-smart agriculture is comparable with that of the woody perennials—at least the additional investment required to establish and maintain the woody perennials is compensated by the range of new revenue streams that can be obtained—for example, production of timber, fruit and fuelwood—as well as the annual crop yield. from Economic Analysis of Agroforestry Systems in the Humid Tropics date:n.d. Another important reason for the relative success of the economics of agroforestry over longer time scales (decades) is its nature of return—the initial capital investments are investments in the future, and years are required to observe such (very slow) returns (Carbon Sequestration Potential of Agroforestry Systems in the Tropics, n.d.).

The overall analysed net-income was USD 2310 ha-1 with a benefit-cost ratio of 3.25 and on an adaptation cost of USD 710 ha-1 under conservation agriculture. This method has minimal resources requirements compared to agroforestry or climate-smart agriculture, however, it does demand an initial investment, and reduced tillage and increased soil cover results in reduced fuel, labour and machinery costs while also seemingly improving yield, thereby increasing profitability over time. Diversification of crops led to a benefit-cost ratio of 3.24, lowest adaptation cost of 620 USD ha^{-1} and a net income gain of 2010 USD ha^{-1}. The other end of that is that the financial investment required for this strategy is very low for smallholders compared to more intensive strategies which may make it more accessible, however, it results in less income being generated from the crop, and thus less potential to boost the welfare of the household (Crop Diversification and Farm Income, n.d.).

Despite registering a net income of USD 2560 ha^{-1}, the net profit of the drip irrigation system was the lowest with a benefit-cost ratio of 2.88 USD.Despite that, drip irrigation had the lower benefit-cost ratio of 2.88 USD and a net income of USD 2560 ha^{-1}. The on-farm adaptation costs associated with the equipment purchase and installation (up to 890 USD ha^{-1}) are comparatively high, although water savings and yield improvements can be as high as 890 USD ha^{-1}. The implication for policy design that emerges from this finding; drip irrigation may be appropriate for conserving water but it may require some form of state subsidy or credit system for its cost-effectiveness (i.e., it is very expensive for smallholder farmers).

Based on the tribalization of all farmer surveys, the major drawbacks that emerged as farmers' problems were: High initial investment (Mean = 4.56 on 1-5 scale) and Limited technical knowledge (Mean= 4.33 on 1-5 scale). Restrictions are stronger for capital-intensive practices such as agroforestry and drip irrigation, which require a greater, but often higher, capital investment than can be made by many small-scale farmers (Olarewaju et al., 2025). This economic analysis highlights the critical need for targeted financial tools – such as subsidized credit lines, result-oriented payments of ecosystem services and input vouchers – to help overcome the cost-effectiveness of implementing the tools and overcome adoption obstacles that prevent adoption at scale.

4.5 Farmer Adoption Constraints

Despite their proven effectiveness in food production, environmental sustainability and economic gains, there are many challenges to the implementation of these approaches on a large scale that need to be resolved for climate-smart agriculture and agroforestry to be fully realised. The need to identify and quantify these constraints is an important part of the comparative evaluation as without the capacity and willingness of farmers to make the adaptations, even the most effective strategies will be ineffective (Barriers and Opportunities for Climate Change Adaptation in the Agricultural Sector a Systematic Review, n.d.-b).

Manification survey carried out in every agro-climatic regions showed that financial constraint and knowledge constraints are always the most formidable constraint for the adoption across all agro-climatic regions. High initial investment was highlighted with a mean importance ranking of 4.56 on a scale of 1-5 and ranked first out of the barriers listed. This is true across a broad range of contexts in agriculture: Drip irrigation, agroforestry and precision agriculture are all labour-intensive practices, and small farmers are less likely to have access to savings and credit facilities and therefore less willing to adopt these practices compared to other farmers (Financial Constraints and the Adoption of Modern Irrigation Technologies in Developing Countries, n.d.). The upfront investments are high, for example in introducing perennial vegetation on farms (relating to agroforestry) or in the drip irrigation system or in the investments in precision technologies adapted to favourable climate change and are higher than the annual income of these households and therefore need additional support instruments outside the farm to overcome the investment gap.

Table 1. Major constraints to the adoption of climate adaptation strategies across five agro-climatic regions, ranked by mean importance score on a 1–5 scale.

Constraint	Mean Score (1–5)	Rank
High Initial Investment	4.56	1
Limited Technical Knowledge	4.33	2
Water Scarcity	4.17	3
Poor Policy Support	3.94	4
Limited Access to Credit	3.82	5
Climate Uncertainty	3.71	6

Limited knowledge of techniques was the second most significant barrier (mean score of 4.33). This limitation is because a lot of the farmers' adaptation activities are complex and based on new skills, like using effective-INPM practices and managing soil health, among others, and in a specific time when the farmers need to adapt when climate conditions change, for example, irrigating or fertilizing in suitable periods (Muriithi, 2021). Adopting climate smart agriculture, conservation agriculture and other novel approaches capable of improving productivity and profitability of conventional agriculture to boost food production amid climate change demands an overall paradigm shift in conception and management which can only be achieved through proper training and extension. The participants of these focus group discussions were hesitant to implement unfamiliar methods because of the uncertainty associated with crop failures or lower yields during the time of transition; which severely affects households with low capacity to deal with the loss of yields (Zulu-Mbata et al., 2016).

The third ranking at 4.17 shows water scarcity due to inadequate amount of precipitation and groundwater resources, particularly in rain-fed and semi-arid areas, facing the agriculture production system (Gautam and Rao, 2008). Interestingly, water scarcity also acts as both a catalyst for many of the adaptation strategies, and as a constraint as some strategies, like drip or rainwater harvesting, do not provide an effective livelihood if there is little water. Under extreme water shortages, it may be possible to see that benefits of even water-conserving strategies are not worth the investment.

The lowest perceived support comes from farmer perceptions of the lack of government programs and institutional frameworks to assist farmers in making adaptation transitions, with an average score of 3.94 and ranking 4th. This also includes the failures to provide adequate subsidization of the climate resilient inputs, the absence of agricultural crop insurance to counter exposure to climate risks, and a failure to enable long-term agricultural planning for stability in investment decisions (Policy Support and Institutional Barriers to Climate Change Adaptation in the Agricultural Sector of South Asia, n.d.). Limited access to credit scores (3.82) which is closely related to the high initial investment hurdle, estimated to be a major factor influencing the decisions of farmers to adapt (Chalchisa & Sani, 2016).

The climate uncertainty was recognized as a unique obstacle (with the mean score 3.71), and was the sixth most cited obstacle. Farmers face the challenge of making investment decisions in the context of high climatic variability and unpredictability (Brown et al., 2026) that this constraint represents. Future climatic changes with uncertain rainfall and temperature may make it less successful to dedicate resources to adaptation since success relies on future climatic conditions. This discovery has revealed the need for better climate information services, and downscaled seasonal forecasts to help agricultural communities make better-informed decisions, while minimizing uncertainty. This will require a suite of solutions at the policy level, with strong links between financial mechanisms, capacity building and institutional change in order to create the enabling environment for the widespread implementation of best adaptation practices.

4.6 Correlation Analysis

The data set of Crop yield, Resilience score, SOC and Farm income were analysed and presented as heat map.The team had the crop yield, resilience score, and SOC & farm income data set analysed using a Pearson correlation and the resultant heat map was presented to the team. The resulting correlation matrix (Table 1) provided quantitative justification of high positive correlation of these variables and thus supported the main result that the most appropriate adaptation strategies are those that help improve agricultural production, environmental protection and economic benefits as well.

Table 1. Pearson correlation matrix illustrating the relationships among four key sustainability indicators across all evaluated adaptation strategies and agro-climatic regions.

Variable	Crop Yield	Resilience Score	Soil Organic Carbon	Farm Income
Crop Yield	**1.00**	**0.89**	**0.83**	**0.91**
Resilience Score	**0.89**	**1.00**	**0.87**	**0.86**
Soil Organic Carbon	**0.83**	**0.87**	**1.00**	**0.80**
Farm Income	**0.91**	**0.86**	**0.80**	**1.00**

The overall results indicated that all the correlation values were positive and significant ranging from minimum of to maximum of for soil organic carbon and farm income and between the yield and the farm income. At farm level a very high correlation between farm income and yield (v. 0.87) seems to follow the basic economic principles of farms and agricultural production, namely that farm income goes up when farm yield goes up; with inputs increased in tandem. The positive correlation between resilience score and crop yield (between farms) of 0.76 indicates the higher the correlation, the more resilient the crop yield would be to climatic perturbations. Interestingly, this knowledge suggests that production risk reduction in the face of stress can be linked with an increased mean productivity, meaning that there seems to be a positive feedback relationship between land stewardship and management of adaptation and productivity in regions facing the climate change.Significant to note is the knowledge that production risk reduction in the face of stress can be linked with an increased mean productivity, indicating that there seems to be a positive feedback relationship between land stewardship and management of adaptation and productivity in regions suffering from stress due to climate change (Tilahun et al., 2023). This correlation identified indicate that investments in resilience-building in practice is not a loss of productivity but enhancement, which has policy implications and suggestions for farmer decision-making practice.

Soil organic carbon (SOC) was the best correlated with resilience score with a clear indication that soil health plays an important role a farm's response to climatic variability. Improved water holding potential in soils, which have high organic carbon, and increased nutrient retention and biological activity at lower soil moisture levels during droughts or heatwaves (Imran, 2025). There are direct links to the enhancement of below ground ecosystem processes and to the accumulation of soil organic matter, which will be specifically targeted by practices with a greater resilience (agroforestry, conservation agriculture)

The other three soil variables of the four analysed were less closely related to farm incomes (); the relationship between soil organic carbon with farm income was the lowest one of the four. This somewhat lower coefficient might be due to the fact that soil carbon will gradually increase over several growing seasons before economic benefits become apparent, with yield responses in soils with improved health being measured after several years (Thierfelder et al., 2017). Despite this, it is clear that there is an economic reason – as verified by this positive association – to encourage soil health as an essential element of adaptation strategies to climate change for farmers.

Based on the positive co-correlations among all four indicators it is shown that the climate adaptation strategies do not create adverse feedbacks among economic, environmental and productivity aspects. Thus, the most effective water strategies are those that can contribute to alleviating the scarcity of water, the lack of nutrients, deterioration of the land and loss of biodiversity all at once. The patterns of correlation thus provide a good statistical foundation for prioritization of multifunctional measures of adaptation rather than individual measures seeking to optimize the different assessment parameters.

4.7 Future Climate Adaptation Projection (2025–2035)

Based on this learning from best practices observed, projection modelling was carried out to estimate future projections of agricultural resilience and agricultural productivity by 2035, again with the assumption of continued implementation of best practices (for adaptation) to the crops. This visionary study emphasizes the gains of long-term investments in climate smart agriculture and agroforestry and assists in understanding the planning time horizon for policies and decision making for farmers (Baruah et al., 2026).

Based on the trends observed in the historical record of the rate of increase in resilience and the yield gains that have occurred across germplasm and varieties, respectively, and based on projections for overall increase in these measures over the next decade, data from the projection model indicate that these trends will continue through the decade, resulting in increased growth rates for both resilience and yield gains moving forward. The climate resilience score will further grow from 74 in 2025, to 94 in 2035, which is a decent improvement of 27% in 10 years as shown in Table 1. This projection considers the progressively adoption of adaptation strategies such as agriculture and agroforestry practices which have become more resilient following this assessment (Climate-Smart Agriculture in South Asia, n.d.), that are known as climate-smart agriculture and are common in agriculture and agroforestry. The proposed climate resilience benefits are cumulative benefits driven by improved soil health, soil water holding capacity and by development of perennials included in these practices.

Table 1. Projected agricultural resilience and average crop yield under continued adoption of optimal climate adaptation strategies from 2025 to 2035.

Year	Climate Resilience Score	Average Yield (t ha^{-1})
2025	74	4.8
2027	78	5.2
2029	82	5.5
2031	86	5.9
2033	90	6.3
2035	94	6.7

Meanwhile, in all regions, the average crop yield (representing 60.6% of yields declining) will rise from 4.8 t ha^{-1} in 2025 to 6.7 t ha^{-1} in 2035, reflecting a 39.6% increase. This is the outcome of increased soil organic carbon, improved use efficiency of water and cultivating stress-adapted crop-cultivars, among large number of farmers (Baruah et al., 2026). In particular, the yield improvement rate is projected to rise a bit in the projection period from 0.2 t ha–1 per year around 2025–35 to 0.4 t ha–1 per year around 2033–35. The same thing that occurs in mature perennial components of agroforestry systems is found in this case in agroforestry, and it's probably a result of the fact that it is a long time before having a positive effect on soil health and productivity as the "outcome" of agroforestry (Economic Analysis of Agroforestry Systems in the Humid Tropics, n.d.).

The size of these gains suggests that further investments in climate adaptation measures can help to significantly reduce the yield difference between the conventional and the more climate-resilient farming systems, especially in areas with low baseline yields, such as rain-fed and semi-arid areas. Obstacles to the project's achievement of these projections include high levels of financial investment requirement, and shortfalls in technical knowledge constraints, both of which occurred during project adoption (Olarewaju et al., 2025). The trajectory of the expected path could be adjusted if policies are required in order to overcome these challenges, as the benefits of adaptation will not be experienced throughout the agricultural system until they are embraced. These projections not only provide an objective target to aspire to, but also a number behind the scene to push the policy-making community towards a quick policy action to scale up the application of climate-smart and agroforestry methods.

Discussion

There are important, theoretical and practical reasons to examine the comparative evidence covered by this study, with specific reference to plans for agricultural adaptation in the face of the increasing pace of climate change. The high positive associations between productive resilience, high scores, high SOC and high farm income theoretically lead to questioning the traditional understanding of 'productivity' vs 'environmental sustainability' tradeoffs in agricultural systems (Antonio et al., 2024). We would say that interlinksages across sustainability dimensions are more a 'synergy' than a 'trade-off' when addressing them in a multifunctional and integrated manner, as in agroforestry or climate smart agriculture. This understanding is developed on the concept of ecological intensification (Weltin et al., 2018) which states that incoming external factors can be decreased while increasing resilience capacity without attaining a loss in yield/economic return. The theoretical connection goes to the idea that sustainability for agriculture should not be cast as an optimization problem but as a design challenge that can be achieved by designing a variety of different synergies with an optimal arrangement of the components.

The findings have profound policy implications for both extension and farmers, and policy-makers. From a prior perspective, the ability of climate-smart agriculture and agroforestry to perform better in each of the dimensions assessed is strong evidence-based reason to prioritize investments in climate adaptation, particularly in rain-fed/cold-stone farming systems where yield gains were realized of 53% and 47%, respectively. Finally, it is important to transfer financial support from agriculture departments and international development programmes towards treatments that will enabled the uptake of available integrated solutions as opposed to the single-component solution with lower resilience scores and GHG reductions for the drip irrigation alone treatment. Secondly, it was discovered that few major issues were creating obstacles to adoption: high initial investment expenditure, and lack of technical expertise, which suggests that careful consideration should be given to policy instruments, in terms of their financial and technical feasibility. These can be used synergically to remove both of these constraints—such as granting, say, cash flow and/or interest-free credit flows conditionally (ie: with conditions of extension programs). Third, the projection modeling findings – that perhaps by that time there would be fewer impacts on resilience between 74 and 94; and fewer impacts on yields between 4.8 and 6.7 t ha-1 – also quantify the compelling argument for going ahead and taking policy action now, rather than waiting for the 2035 horizon.

A few caveats to the method should be noted when interpreting these results, however. The relationship between adoption of adaptation strategies and potential difference in performance leading to causal inferences for this study, however, could be conducted using a cross sectional comparative approach (Sharma & Patel, 2026). This bias is partially mitigated by statistical controls and multiple regression but unknown differences in the management of the farm, soil structural attributes and/or perhaps the types of past agricultural uses on any specific farm could account for the significance of strategy given an identified difference in farm performance. Additionally, the agro-climatic regions are not comprehensive of all agricultural environments, particularly the cold semi-arid region and highland environments which may have varying effects on adaptation approaches. Self-reported farmer survey information to gather adoption constraint data may have social desirability bias because farmers might over-report the influence of some barriers (such as high costs) and under-report the influence of other barriers (such as risk aversion). Furthermore, the adoption rates projected in the period 2025–2035 were linear, and the climatic conditions were assumed to remain unchanged; in reality, both the rate of adoption and the climatic conditions might turn nonlinear and be influenced by unpredictable market changes and climate change, as well as by changing policy situations (Olesen et al., 2007).

Conclusion

Comparative evaluation of adaptation options to climate change to find out the most productive, environmentally sustainable and economically viable pathways for agri-culture in various agro-climatic regions. The integrated and multifunctional strategies received good support for the primary goal of creating more effective interventions than the single-component strategies. Overall, the most favorable solutions were weak and clear, when it came to resistance: the best solutions were those that offered high levels of resistance, increased yields, and the most desirable benefit-cost ratio, and reduced GHGs and improved soil health in addition. The key achievement of this research is the systematic evidence to prove that these two steps have complimentary not mutually exclusive effects on all sustainability aspects, arguing the views that productivity and environmental aspects are at odds. Additionally, the finding that the adaptation gains are highest where rainfall is insufficient to support agriculture and that high investment and limited technical knowledge are the main drivers to avoid adaptation, provides policy guidance on how best to target policy measures.

Future research to quantify the farm-level influence of an adoption ethos on the potential trajectory of farm outcomes over time using longitudinal-panel data would benefit because of the time lag between farm-level improvements in soil health and the economic return from these improvements. In general, the research, testing and evaluation of farmer field schools, digital extension services and peer-to-peer learning networks to determine their efficacy in closing the technical knowledge gap outlined above is also important.

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