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**Climate-Resilient Agroecosystem Management Enhances Sustainable
 Crop Production: A Multi-Site Field Evaluation of Integrated Strategies**

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Abstract: We field tested the feasibility of integrated actions for managing agroecosystems sustainably to adapt agriculture to climate variability and change in multi-location and multi-variable agricultural research fields of 300 experimental plots and 20 research farms. This was a randomised complete block design experiment with three replications conducted with ten interventions, namely conservation agriculture, crop diversification, agroforestry, mulching, drip irrigation, integrated nutrient management, integrated pest management, climate-resilient varieties, rainwater harvesting and precision fertiliser application. Through two consecutive cropping seasons, the data were collected and analysed based on analysis of variance, multiple linear regression and PCA. We found that adoption of climate-resilient practices reduced nutrient-use efficiency by 20.9%, improved water-use efficiency by 22.1%, improved soil organic carbon by 24.8%, reduced pest incidence by 18.7% and increased the grain yield by 29.4% when compared with conventional practices. Overall, the multiple linear regression model explained 76.3% of the variance in sustainable crop production, with the soil organic carbon (SOC) ($\beta = 0.45$, $p < 0.001$), water-use efficiency (WUE) ($\beta = 0.39$, $p < 0.001$), integrated nutrient management (INM) ($\beta = 0.34$, $p < 0.001$), and types of climate-resilient varieties (CRV) ($\beta = 0.29$, $p = 0.002$) emerging as the most important predictors of performance. Moreover, principal component analysis showed that the three main components of soil fertility and water management, as well as crop productivity, accounted for 82.4% of the total variance. There was a significant positive relation of the climate resilience index with crop productivity ($r = 0.84$, $P < 0.001$).

Keywords: Climate-Resilient Agroecosystems, Sustainable Crop Production, Integrated Farm Management, Agroecological Adaptation, Multi-Site Field Evaluation

Introduction

The current climate change, characterised by an unprecedented acceleration in the rate of change, accompanied by a rise in extreme weather events, variation in precipitation and temperature, is creating new challenges to global agricultural systems that could have negative impacts on food security on a global scale (Altieri et al., 2015). The development of production systems that can withstand the stresses herein while maintaining the environmental integrity has never been more critical. Traditionally, high-yielding varieties, intensive tillage, monocrop and overuse of synthetic inputs have been the hallmark of conventional agriculture and have enabled high yields, but at the cost of environmental degradation, particularly of soil, water and biodiversity (Asare et al., 2025). The systems are highly sensitive to the climate shocks, and there is an urgent need for a paradigm change that would enable more resilient and sustainable systems. The agroecosystem management that is resilient to climate change is a viable option which incorporates ecological management with agronomic innovations for improved productivity and adaptability (Sinclair et al., 2019). These include a range of techniques that together reduce dependence on external inputs by increasing organic matter and optimising soil and water use and providing resilience to environmental stresses – the combination of which are known as conservation agriculture, crop diversity, agroforestry, integrated nutrient management, and precision water management (Joshi et al., 2026). The idea of the agroecosystem, a holistic ecological system where the farm is more than a set of production elements, can be a good guide for understanding how these interventions' synergy comes about (Altieri et al., 2024). Nonetheless, theoretical developments in the area have taken pace, but much of the empirical work involving multi-location field testing through varying agroecologies is still to be done.

The entire agricultural landscape involved in this study includes a total of 20 different agroecological zones, with each having its own climatic conditions, soils, and crop/agricultural practices (Roy et al., 2023). These areas fall under various climatic conditions of precipitation, climatic conditions of precipitation, temperature and soil types ranging from arid to humid tropics, sandy soils to highly weathered laterite soils (Fischer et al., 2000). Understanding the performance within this heterogeneity is key to making context-specific recommendations on climate-resilient interventions that can be scaled. Additionally, the traditional farming conditions reported here as representational baseline farming conditions are based on the conditions used by the majority of farmers in each zone and are therefore realistic conditions for comparative purposes of the relative strength of alternative farming methods (Bogaard et al., 2018). The key idea for this work was to gain much more – in terms of agronomic performance, soil health, water-use efficiency and system resilience – from combining multiple climate-resilient practices into a farming system than by relying on conventional farming practices alone. Specifically, we hypothesised that the introduction of conservation agriculture practices, crop diversification, agroforestry, and integrated nutrient management and precision irrigation systems would have a greater impact than their implementation alone. The main goal was to measure the extent of these benefits in various agroecological situations and to determine which factors were the most important drivers of sustainable crop production. An

indirect goal was to create composite indices, such as the climate resilience index, soil health index, and sustainability performance index, that could be used as tools to measure and compare management systems.

The findings of this study have several key contributions to the climate change and agriculture literature. First, it is an edible application study with a large scale and multi-site and therefore a wide range of agroecological zones, so that it is easier to generalise the results. Second, it uses a full toolbox of analytical techniques to delve through the intricate links between management practices, environmental parameters and production results, such as statistical analysis of variance, multiple linear regressions and principal component analysis. Third, it shows that production and sustainability outcomes can be made to go hand in hand by producing a climate resilient intervention that improves more than one facet of system performance – beyond just yield – including soil health, water conservation and carbon sequestration. The implications of these findings for agricultural policies, extension services and farmers' decisions in climate change sensitive areas are immediate. Section 2 presents the literature related to agroecosystem management and its impact on crop production and environmental consequences as a requirement for the more efficient management of agroecosystems in future climate change conditions. The experimental design, study sites and data collection and statistical analysis techniques are described in Section 3. The differences between climate-resilient and conventional regression and principal component analyses are presented with field experiment results in Section 4. The results are presented with implications, limitations and suggestions for future research in relation to available theories. A summary and recommendations for policy and practice are given at the end of Section 6.

Literature Review

The notion of “climate-resilient agriculture” has progressed significantly during the last 20 years from theory to tested in practice management strategies. Altieri et al. (Altieri et al., 2015) proposed that the principles of agroecology, such as water harvesting, soil organic matter management, and biodiversity enhancement, could buffer farming systems to climate shocks and still be productive. The Food and Agriculture Organization also developed this concept and presented climate-smart agriculture as a multi-faceted strategy to address food security, adaptation, and mitigation (Branca et al., 2011). However, it has been a long time since they have been used in observable basic school outcomes in a variety of settings.

Numerous studies have focused on learning about single practices that are resilient to climate change. Conservation agriculture (CA) (minimum tillage, permanent soil cover, and crop rotation) has been a research interest of great interest related to soil health and water conservation. However, Hobbs et al. (Hobbs et al., 2007) showed that in temperate areas no-till systems are able to cause an increase of 0.3–0.6 Mg ha⁻¹ yr⁻¹ in soil organic carbon, while this benefit is more variable in the tropics because of the rapid decomposition rates. Similarly, crop diversification has been shown to provide natural enemy turnover and conservation effect and complementary resource use to stabilize yield (Sridhar et al., 2025). Moreover, the integration of trees in the agricultural landscape in agroforestry would benefit from the microclimate regulation, nutrient cycling, and carbon sequestration (Jose, 2009).

Water management has been especially the focus with respect to climate resilience. For example, drip irrigation can increase water-use efficiency by 30–50%, compared to conventional surface irrigation, and also minimize the loss of water through soil evaporation and deep percolation (Venot et al., 2017). In the semi-arid regions, techniques of rainwater harvesting like contour bunds/crofts, check dams, and rooftop catchment have been shown to be effective in safeguarding crop production from rainfall variability (Oweis et al., 2012). The use of long-term nutrient management practices like integrated nutrient management of organic amendments and inorganic fertilizers can be used to enhance soil fertility without causing significant environmental impacts in terms of GHG emissions associated with inorganic N production (Paramesh et al., 2023).

Although individual practices have been well studied, the combined effects of several practices in integrated management systems to tackle climate-resilient issues are less known. Giller et al. (Giller et al., 2009) warned that the advantageous effects of conservation agriculture can be context-specific and can be difficult to achieve without joining with other complementary measures, like keeping the crop residues and managing weeds. This finding highlights the need to consider integrated approaches as opposed to stand-alone interventions. Moreover, most research has been done at only one location or in very limited agroecological zones, and so the results may not apply to a variety of agroecologies (Akinagbe & Irohibe, 2014).

The present study sets out to address these gaps by using a multi-site experimental design, testing 10 interventions that are climate resilient either individually or in combination in 20 agro-ecological zones. There have been few studies that have measured soil health indicators, water-use efficiency, pest dynamics, and the potential for carbon sequestration simultaneously, making this the first study to do so, enabling a comprehensive assessment of the performance of the systems. In addition, we created composite indicators like the climate resilience index and the sustainability performance index that provide a new paradigm to evaluate management systems in terms of multiple dimensions of performance. The holistic approach distinguishes our research from previous studies and offers a more comprehensive understanding of the optimization of climate-resilient strategies for various agriculture practices.

Materials and Methods

Study Design and Experimental Setup

The study design was experimental and cross-sectional in the field to evaluate the effectiveness of the climate-resilient agroecosystem management strategies for sustainable crop production. The study was carried out on 20 agricultural research farms and farmers' fields, which are scattered in different agroecological zones, ensuring the diversity of the geographic and environmental factors in the assessment process. A randomized complete block design (RCBD) with three replications of each treatment combination was used to design 300 experimental plots, which provided adequate statistical power to determine treatment effects while considering spatial heterogeneity within each location.

Ten strategies were used in experimental treatments to cope with the climate-constrained environment: conservation agriculture, crop diversification, integration with agroforestry,

mulching, drip irrigation, integrated nutrient management, integrated pest management, planting of climate-resilient cultivars, rainwater harvest, and precision application of fertilizers. The treatments were applied in accordance with the standard procedure already developed for the agroecological situation. Conservation agriculture comprised reduced tillage (<20% of conventional tillage intensity) and permanent soil cover (3-5 Mg ha⁻¹) with crop residues and crop rotation patterns in accordance with the local conditions. The crop diversification treatments included diversification module, additive series, and replacement series designs, and the number of species ranged from 2 to 4 per plot. The tree species used included *Gliricidia sepium* and *Faidherbia albida*, which were planted in agroforestry in different ways, either at the edge of the field or in a scattered arrangement, at densities of 100-200 trees ha⁻¹.

Data Collection and Laboratory Analysis

Field observations were made for two successive crop seasons, covering the major crop growth period for each agroecological zone. Soil samples taken from each plot at the two depths (0–15 cm and 15–30 cm) were measured with a soil auger; five subsamples were composited within a plot to represent within-plot variability. The samples were air-dried, sieved at 2 mm, and analyzed for soil organic carbon by the Walkley-Black dichromate oxidation method, soil pH in soil water suspension (1:2.5), and available N by the alkaline permanganate method. Available phosphorus was extracted by the Olsen method (neutral to alkaline soil) and Bray-1 (acid soil), and potassium was extracted by ammonium acetate extraction and measured by flame photometry.

Key phenological stages were evaluated for crop growth parameters. The height (from soil surface to top of main stem) was measured for 10 randomly selected plants in each plot. Leaf area index (LAI) per plot was measured at three locations at solar midday under clear sky conditions and then averaged, using a portable ceptometer (AccuPAR LP-80, Decagon Devices). The youngest fully expanded leaf of 5 plants/plot was used for measuring the chlorophyll content with a chlorophyll meter (SPAD-502 Plus, Konica Minolta). Water-use efficiency (WUE) was based on the ratio of grain yield to total evapotranspiration, which was estimated from the FAO Penman-Monteith equation and measurement of soil water balance from weekly neutron probe readings.

Occurrence of pests and disease symptoms was determined by visual scouting on each plot using diagonal transects, and the number of damaged plants was recorded for major arthropod pests and disease symptoms. Grain yield, which was based on test weight at 14% moisture, was measured at physiological maturity by cutting a 4 m² central area from each plot, threshing, cleaning, and weighing the grain. Production of biomass was determined by picking aboveground plant material in the 1 m² subplot, drying it at 65°C for 72 hours, and weighing the dry material. Allometric equations for tree biomass of agroforestry treatments and the IPCC default method for soil carbon stock changes as a function of measured soil organic carbon concentration and bulk density were used to estimate the carbon sequestration potential.

Data Preprocessing and Quality Assurance

The data collected were preprocessed extensively to guarantee the quality of the data and the validity of the analyses. Plots with more than 20% missing data for each variable measured were excluded from the data set. The multivariate imputation by chained equations (MICE) algorithm was then used to impute the missing values for the remaining observations by creating plausible values with the joint distribution of observed variables. Outlier detection was done using the method of interquartile range (IQR), with low outliers being marked as $Q1 - 1.5 \times IQR$ and high outliers being marked as $Q3 + 1.5 \times IQR$; the student was then asked to evaluate each one and, if found to be measurement error, replace it with the median value of the corresponding treatment group.

Data normalization was done on the variables with different measurement scales to enable comparative analyses. Each of the variables was normalized using the min-max method $X_{\text{norm}} = (X - X_{\text{min}}) / (X_{\text{max}} - X_{\text{min}})$ with values in 0-1. Levene's test was used for homogeneity of variance, and the Shapiro-Wilk residuals normality test was used to evaluate the normality of the residual values. If these assumptions were not met, then suitable transformations (logarithmic or square root) were used. Quality assurance was carried out by a number of different laboratory validation processes, such as analyzing 10% duplicate samples and using certified reference materials, as well as by taking part in proficiency testing programs offered by different laboratories.

Statistical Analysis and Evaluation Indicators

To assess the treatment effects and determine important predictors for sustainable crop production, a statistical analysis was used in a multi-faceted way. For all treatment groups, the means, standard deviations, and coefficients of variation were calculated for all measured variables. Data were analyzed using one-way analysis of variance (ANOVA) to determine differences among the ten climate-resilient treatments as compared to the conventional control and two-way analysis of variance (ANOVA) to determine interactions between treatment and agroecological zone. Pairwise differences between means were determined using ANOVA, and Tukey's honestly significant difference (HSD) post hoc test was used.

Pearson correlation analysis was used to determine the association between the different variables measured and the composite indices. The regression equation for the sustainable crop production and the predictor variables was of the form: sustainable crop production was modelled as a multiple linear regression of the predictor variables.

$$[Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \epsilon]$$

Y = sustainability performance index, β_0 is a constant, β_i are the regressor coefficients of the i -th predictor variable (X_i), and ϵ is the random error term. A stepwise procedure was used to select these variables; variables were entered with P -values of <0.05 and removed from the model with P -values of >0.10 . The degrees of freedom of the correlation matrix of standardized variables were reduced using principal component analysis (PCA), and latent factors were extracted from the correlational variation. Eigenvalues greater than 1.0 were kept, and varimax was rotated for clarity.

Composite indicators of evaluation were developed, which encapsulate several aspects of system performance. The crop productivity index (CPI) was calculated as the geometric mean of normalized grain yield, biomass production, and crop emergence percentage. The climate resilience index is a random mix of the normalized values of water-use efficiency, pest incidence (inverted), and carbon sequestration potential. The soil health index comprised soil organic carbon, available soil N, P, K, and soil pH. The sustainability performance index was determined by taking an average of the crop productivity index, climate resilience index, soil health index, and resource use efficiency. All statistical analyses were performed in R version 4.3, SPSS 29, SAS 9.4, Microsoft Excel, and ArcGIS Pro (for visualization of spatial data).

Results

The following results relate to a detailed study with 300 experimental plots over two successive cropping years. The results are summarised first in order to describe the experimental microclimate, then the effect of the evaluated management practice on sustainable crop production and soil quality, and the values of regression, correlation and principal component analysis were carried out to assess the contribution of main parameters that were evaluated in the study.

Field Characteristics and Experimental Setup

This involved all 300 experimental plots going through rigorous quality control procedures, with the results retained for the final analysis. The experimental network comprised 20 agroenvironmental zones (AEZs) that can be linked to various climate, soil and farming system conditions. Several zones had an annual precipitation of less than 500 mm, while others had more than 1500 mm, and there were even differences in the temperature regimes, growing season, and initial soil fertility status. Data have been collected over two back-to-back cropping seasons to enable such temporal replication and thus account for inter-annual climatic variability specifically for this study – variations related to the rainfall distribution and extremes of temperature linked to the climate change scenarios.

For the ten climate-resilient management strategies considered in this study, the treatments were all repeated at all sites, but with some regional variations in the choice of crop species and planting dates. Treatments for conservation agriculture consisted of tillage reduction (<20% of conventional tillage), crop residue rate (3-5 Mg ha⁻¹) and crop rotation (use of at least three species in two seasons). Crop diversification treatments involved intercropping with two to four species, and agroforestry integration involved the introduction of trees at 100–200 trees ha⁻¹ at the field borders. The mulching treatments were applied at a level of 5 Mg ha⁻¹ dry weight mulch, and irrigation systems were drip, which supplied 80% of the crop evapotranspiration demand (ET_d). The integrated nutrient management involved applying 75% of recommended mineral fertilisers and 5 Mg ha⁻¹ farmyard manure (organic amendments), and the integrated pest management involved applying pesticides when the threshold levels are exceeded and biological control agents were used. Climate-resilient crop varieties chosen from the national variety release list were drought-tolerant and pest-resistant ones, while the rainwater harvesting structures comprised contour bunds, and the micro-catchments were

considered to gather and store the rainwater. Variable-rate technology (VRT) based on soil sampling by grid was used with precision fertiliser application.

A 30-treatment-replication (10 treatments $\times$ 3 replications) RCB design was used. The size of each plot was 5 m $\times$ 10 m (50 m²), including 1 m buffer areas between plots to reduce edge effects and treatment interference. The conventional farming system was used as a control farming system and had been used according to the local farming standard practices, such as conventional tillage (moldboard ploughing to 25 cm soil depth), monocropping with the local dominant crop species, surface irrigation where applicable and the full rate of synthetic fertiliser application as recommended by soil testing. The design was such that the climate-resilient system was directly compared with the conventional system while keeping the rest of the design parameters unchanged, which was also demonstrated as a strong framework for evaluation of the treatment effects.

The characterisation of soils before the implementation of the treatments showed that the soils were very heterogeneous within the 20 agroecological zones. Soil organic carbon (SOC) mean value varied from 0.4% for degraded sand soil of semi-arid regions to 2.8% for fertile soils of alluvial regions of humid regions, with an average value of 1.2% in all the soils studied. The soil pH varied between 4.8 in highly weathered tropical soils and 8.2 in calcareous soils in arid zones, while the available N, P and K content varied from 15 to 85, 3 to 28 and 60-320 kg ha⁻¹, respectively. This baseline variability posed difficulties in the statistical analysis of the variability, but it could also be used to evaluate the robustness of the climate-resilient interventions through different potentially occurring initial conditions, making results more generalisable. Considering the different real-life situations, the multi-site, multi-treatment and multi-season experimental design served as a good benchmark to assess the performance of the agroecosystem management strategies to cope with climate change.

Crop and Soil Performance

Adoption of climatic resilient agroecosystem management practices (CARMP) led to important benefits compared to the conventional farming system for several crop and soil performance criteria. Another significant product used to gauge the productivity of crops and grain production favoured the treatments compared to the conventional of 3.2 Mg ha⁻¹ by 4.1 Mg ha⁻¹. This yielding gain was similar across all 20 agroecological zones, with gains between 18.7% in the semi-arid zone of sandy soils and 36.2% in the humid tropical zones, where yield was higher. The observed yield increase was due to the synergistic effect of the combination of conservation agriculture, mulching and integrated nutrient management, which resulted in improved soil moisture retention, increased nutrient availability and reduced pest management.

Regarding soil organic carbon, which is one of the most important soil health and fertility parameters, the average soil health in the conventional management plots was 1.2%, while the 'climate-resilient management' increased the soil health up to 1.5%, an improvement of 24.8%. The upturn in carbon sequestration was also observed in the treatments that involved conservation agriculture and agroforestry integration, which, in this case, increased the amount of carbon sequestered in surface and subsurface soil layers. The improvement in soil organic carbon is significant, as it not only indicates that nutrient cycling capacity has improved but

also that soil structure, water infiltration ability, and microbial activity have improved, which will help achieve long-term agricultural sustainability (Joshi et al., 2026). Moreover, the longer that these know-how principles are followed, the greater the amount of SOCC produced, suggesting that the longer duration of these practices used may lead to increased benefits in the future.

Water-use efficiency of the climate-resilient management conditions surpassed that of conventional management conditions by 22.1% ($10.0 \text{ kg ha}^{-1} \text{ mm}^{-1}$ of treated conditions compared to $8.2 \text{ kg ha}^{-1} \text{ mm}^{-1}$ of conventional conditions). This was primarily a consequence of the adoption of drip irrigation and mulching, which reduced the loss of soil particles from the surface as a result of evaporation and facilitated water use in an efficient manner at the root zone of the crop. Trees also helped with microclimate control in agroforestry treatments by lowering the wind speed and canopy temperature and thus further lowering the rate of evapotranspiration. The increase in WUE becomes relevant in times of water scarcity and water climate variability and illustrates that water-use efficiency can not be a trade-off between production and water use. Using less water does not necessarily mean a decrease in production, and climate-resilient practices can maintain or even increase production levels while using less water (Venot et al., 2017).

The management based on climate-resilient technology managed to decrease the plant percentage with pest incidence (where there was visible damage from an arthropod pest or symptom of disease) by 18.7% in comparison to conventional management. The decrease was particularly high in crop diversification + IPM treatments, which also tended to yield the most diversity in the crops, the least pest host-finding behaviours, and/or the most natural enemy habitat. The observed reduction of pest pressure was further attributed to the introduction of climate-smart crop varieties, which were bred to withstand local pest complexes. The decreased incidence of pests lowered reductions in yield and decreased the need for synthetic pesticide use, which lowers production costs and the amount of contamination of the environment.

Nutrient-use efficiency (NUE) was expressed in yield of grain per unit of nutrients (N, P, and K) uptake. It was 20.9% higher under climate-resilient management. Adoption of integrated nutrient management practices (INMPs) — organic amendments and reduced applications of mineral fertiliser — mainly contributed to this improvement. The application of organic amendments boosted the activity of soil microbes and soil nutrient mineralisation, while the application of mineral fertilisers through precision farming allowed nutrients to be supplied to the crops simultaneously to the nutrient mineralisation needs and reduced nutrient losses due to leaching and volatilisation. The potential for enhanced nutrient use efficiency has profound implications for economic and environmental sustainability, enabling significant reductions in costs associated with fertiliser use while aiding in mitigating nutrient run-off and water pollution (Paramesh et al., 2023).

Together these results show that management strategies for agroecosystems can be designed that can enhance multiple aspects of both crop and soil performance, thus questioning the common perception of the need for compromising between productivity and environmental sustainability. As gains with grain yield, soil organic carbon, water-use efficiency, pest

suppression and nutrient-use efficiency were observed across the different agroecological zones (AEZ), much of these can be scaled up to other zones and adjusted to local conditions. These improvements (18.7%–29.4%) demonstrate the potential of the holistic management approach for addressing the problems of food insecurity and environmental degradation under increasing climate stresses.

Sustainable Production Outcomes

So, the results of the sustainable production outcomes were measured by the composite indices that were constructed from different aspects of the system performances as measured by individual performances. The SPS was significantly increased by 21.6% calculated using normalised crop productivity, water-use efficiency, soil health, carbon sequestration and resource-use efficiency compared to conventional systems. This composite instrument is an indicator of the performance of the management measures with regard to both productivity and environmental protection and resource conservation in the longer term.

Grain production rose by 29.4% from the mean of the conventional plot (3.2 Mg ha^{-1}) to the climate-resilient practices plot (4.1 Mg ha^{-1}), which is an essential aspect of sustainable production. This yield increase was found in all 20 agroecological zones, with the increases ranging from 18.7% in the zones of semi-arid conditions and high sand content to 36.2% in the humid tropical zones of high baseline fertility. The entire improvement in yield was attributed to the interaction of the combination of conservation agriculture, mulching and integrated nutrient management practice (Altieri et al., 2015).

Overall, the water-use efficiency (which is an important indicator of water-saving under climate stress) was seen to have improved from 8.2 to $10.0 \text{ kg ha}^{-1} \text{ mm}^{-1}$ in conventional systems and treated plots, respectively, representing a 22.1% gain. This enhancement was made via drip irrigation and mulching, which reduced the amount of water lost from the top of the soil and increased water available in the crop's root system (Venot et al., 2017). The beneficial effect of the trees was also observed in the agroforestry treatments, where the trees regulated the microclimate, including the decreased temperature of the canopy and wind speed, which reduced the evapotranspiration rate. This is of particular importance in the context of greater climate variabilities and is proof that practices which are climate resilient can sustain or even boost productivity with lower water use.

When managed for climate resilience, the soil health, defined by soil organic carbon, available nitrogen, phosphorus and potassium and soil pH, improved 24.8%. The application of conservation agriculture under both agroforestry integration and tillage reduction scenarios resulted in greater surface and subsurface soil carbon sequestration benefits compared to the treatment without agroforestry integration and tillage reduction (Joshi et al., 2026). With improvement of soil structure, water infiltration and microbial activity, treated plots with an average SOC of 1.5% versus conventional systems with an average SOC of 1.2% have increased capacity to cycle nutrients to sustain long-term agriculture crop production.

Using allometric equations developed for computing biomass of trees in agro-forestry treatments and the default method estimated by IPCC for evaluating soil carbon stock changes,

the carbon sequestration potential was found to be 18.5% higher under climate-resilient agroforestry treatments' management. The greatest benefits were found for agroforestry, which featured tree biomass increments of 0.8–1.2 Mg C ha⁻¹ year⁻¹ compared to usual practices. The mulching combined with conservation agriculture practices was also a factor that contributed to lower soil disturbance and higher soil organic matter inputs that, in turn, resulted in a higher soil functioning as a carbon sink (Jose, 2009).

Under the climate-resilient management, there was an increase in the use efficiency of water, nutrients and energy inputs, leading to an increase of 21.6% in resource use efficiency. This enhancement was greatly contributed to by the integrated nutrient management practices (INMP), which included the use of organic amendments and the reduction of mineral fertiliser use, and precision irrigation (PI), which optimised delivery based on crop requirements (Paramesh et al., 2023). Efficient use of resources is not only economically sustainable but environmentally sustainable too – because it is cost-effective at reducing the use of costly resources as well as nutrient runoff and water pollution.

The sustainable production outcome is summarised in Table 1 and depicts the percentage difference between sustainable management and conventional management in terms of each indicator.

Table 1. Sustainable production outcomes under climate-resilient agroecosystem management compared to conventional farming systems.

Indicator	Improvement (%)
Grain Yield	+29.4
Water-Use Efficiency	+22.1
Soil Health	+24.8
Carbon Sequestration	+18.5
Resource Use Efficiency	+21.6

Together, these results illustrate how promoting climate resilience through agroecosystem management can also achieve multiple improvements in sustainable production—without having to trade off productivity for the environment. The improvements (18.5% to 29.4%) in this study should serve as a reminder of the potential of integrated management approaches to deal with the two main problems of food security and environmental degradation, especially in the era of climate change that calls for adaptation and resilience. This uniformity across different agroecological zones points towards wide-spread generalizability and adoption of these practices in different contexts, which is critical to establish an evidence-based agricultural policy and practice.

Regression Analysis

To determine the main factors contributing to sustainable crop production under climate-resilient management, a multiple linear regression was done using the sustainability

performance index as the dependent variable. Management practices and resource-use indicators were included in the model with a full complement of predictor variables that covered soil properties. In order to minimize the variables after stepwise variable selection, it was found that four were significant and had a high amount of variance explained by the sustainable production outcomes.

The final regression model was statistically significant ($F_{4,295}=237.4$, $p<0.001$), accounting for 76.3% of the variance (R^2) and nearly 76.0% of the adjusted variance (Adjusted R^2) in the sustainability performance index's (I) total variance. This implies a high explanatory power because most of the systematic variation in sustainable production is accounted for by the selected predictors to explain the variability and differentiate between the huge number of different agroecological backgrounds used for this study. Normality (Shapiro-Wilk $W=0.992$ and $p=0.124$) and homoscedasticity (Breusch-Pagan test $\chi^2=4.87$ and $p=0.301$) were both assumed and tested to assert the validity of the results using regression.

Soil organic carbon showed the highest SR (standardized regression) coefficient; this indicates that the sustainability performance index (SPI) increases 0.45 SD if soil organic carbon increases 1 SD while all other factors are kept constant. As mentioned in earlier research, the organization of soil organic matter is also vital to sustainable agriculture growth, as it impacts soil construction, water-holding potential, nutrient cycling (Elwunegbey et al., 2021), and so on. Since soil organic carbon stock has high predicting capacity, the management practices that are recommended to increase the soil carbon stocks, such as conservation agriculture, mulching, and agroforestry, are very important to reach the sustainability targets.

Water-use efficiency (WUE) ($\beta=0.39$, $p<0.001$) was the second most important predictor, illustrating the critical importance of water management in the establishment of climate-resilient systems. This result is like the results for analyses of drip irrigation and rainwater harvesting that have shown that improved WUE can reduce water use while raising yield simultaneously (Venot et al., 2017). This prominent contribution of water-use efficiency in the regression equation indicates the need for integrated water-management practices that would improve water-use effectiveness by the time of water use and the water use per unit area of crop, especially in the water-scarce climate zones.

An integrated nutrient management (iNM) plan ($\beta=0.34$, $p<0.001$) was another predictor identified, which indicates the need for achieving nutrient balance to ensure sustainable production. This finding supports the concept of increasing the use efficiency of nutrients in conjunction with maintaining soil fertility through organics as well as mineral fertilizers (Paramesh et al., 2023). From the results of our study, we were able to conclude that integrated nutrient management does have its positive impact on sustainability, whether from the root or by affecting soil health and soil microbial activity.

There was also a smaller but significant positive association between the sustainability performance index (CRI) and climate-resilient crop varieties ($\beta=0.29$, $p=0.002$). This result indicates that the potential of genetic improvement, relating to stress resistance (in this case drought resistance) along with other pertinent traits (e.g., pest resistance and heat resistance), can contribute significantly to sustainable production output, particularly in the context of

climatic variability. The inclusion of climate-resilient varieties in the regression model is a good example of the contribution of the crop breeding program in developing new crop varieties to face future climate scenarios (Altieri et al., 2015). The regression base values and level of significance are shown in Table 2.

Table 2. Multiple linear regression results for predictors of the sustainability performance index.

Variable	Standardized β	p-value
Soil Organic Carbon	0.45	<0.001
Water-Use Efficiency	0.39	<0.001
Integrated Nutrient Management	0.34	<0.001
Climate-Resilient Crop Varieties	0.29	0.002

Other factors were also taken into account during the regression analysis but failed to be significant and were excluded from the final model, like incident of pest, soil pH, soil nutrient, and so on. This result pointed out that while these variables may have an impact individually on the disturbance absorbing capacity of the system while maintaining a production, their impact came through strongly the important drivers pointed out by the model. Thus, the effects of crop diversification on sustainability can be mediated, for example, by SOMc and WUE without having direct effects.

This model demonstrated very robust gaining power and showed a high explained variance value ($R^2=0.763$), which differs from another model that explained that the hypothesis that integrated climate-resilient management strategy contributes to sustainable crop production by multiple steps has been well supported by the empirical values. A set of features, such as soil organic carbon, water-use efficiency, integrated nutrient management, and varieties with climate resistance, could make a stark difference, as they can potentially be the most influential. This puts emphasis on soil health and water optimization, nutrient balance, and stress-tolerant crop varieties as vital components of any agenda to develop stress-tolerant agricultural systems.

Correlation Analysis

For 300 experimental plots, Pearson correlation analysis was carried out between key performance indicators and composite indices to gain a deeper understanding of the interrelationship between them. This analysis gave insights on the strength and significance of bivariate (pairwise) association between the measured variables to understand the underlying structure of the associations that act in favor of sustained crop production under climate-resilient management.

The climate resilience index was correlated with crop productivity, which showed a good positive relationship with $r=0.84$ and a p value<0.001. The outcome indicates a strong link between stress resistance to climate change (increased water-use efficiency, decreased pest incidence, and improved carbon sequestration potential) and increased yield. The correlation suggests that climate resilience and productivity are not necessarily conflicting objectives but that well-managed agroecosystems tend to promote features of climate resilience and

productive systems. This result corroborated the theory proposed by Altieri et al. (Altieri et al., 2015) which explained how agroecological practices resulted in increasing ecosystem functions, which in turn had a positive impact on productivity and resilience.

The soil health index had positive relationships with water-use efficiency ($r = 0.79$, $p < 0.001$) and carbon sequestration ($r = 0.75$, $p < 0.001$). Both associations emphasize the important role of soil organic matter in the soil's role in providing multiple ecosystem services. Thus, greater pressure/excess of water in the soil will be beneficial for water use efficiency that can be achieved by maintaining high organic carbon content in the soil, which is reflected in lesser irrigation frequency and intensity (Joshi et al., 2026). Further, the strong relationship between soil health and carbon sequestration stresses that practices that sequester soil organic carbon are improving soil fertility (e.g., conservation agriculture and mulching), and practices that result in a decline in soil organic carbon are also resulting in a decline in soil health.

Furthermore, a strong positive correlation was found between the sustainability performance index and the climate resilience index ($r=0.81$, $p<0.001$), indicating that these two composite indexes provide the two sides to a dimension of performance on a system. This finding suggests that there is good proximity between the sustainability performance index and the application of the concept of climate resilience that is composed of crop productivity, water-use efficiency, soil health, carbon sequestration, and resource use efficiency. This correlation gives support that the use of composite indices can be a good problem diagnosis tool in analyzing and comparing management systems.

The relationship between integrated nutrient management and the sustainability performance index was positive and significant ($r=0.68$, $p<0.001$), and this practice was one of the positive ones in the regression that led to the identification. Similarly, there was a positive association to yield, using climate-resilient crops ($r=0.62$; $p<0.001$). This illustrates the role genetic improvement plays in this changing climate for productivity. The correlations highlight the importance of management practices and of the genetic resources for developing climate-smart agriculture.

When, on the other hand, the correlation between pest incidence and the climate resilience index was negative (-0.54 , $p<0.001$), showing that the more resilient the system, the lower the pest incidence. This emphasizes the importance of IPM as a component of climate-resilient strategies, as pest outbreaks can result in loss of productivity, along with loss of system stability (Sridhar et al., 2025). There is also a negative correlation between pest occurrence and the climate resilience index, suggesting agroecological practices (diversification, agroforestry) that also promote the interest in biodiversity may also indirectly contribute by reducing pests through natural enemy conservation and habitat disruptions.

Moderate positive correlations were also found between the soil organic carbon and available nitrogen ($r=0.58$, with a significance of $P<0.001$) as well as between water-use efficiency and grain yield ($r=0.63$, with a significance of $P<0.001$). They all follow sound principles of agronomic testing: soil organic matter as a source of plant nutrients and the relationship of WUE with biomass accumulated/yield formed. The correlation between each other was found

to be moderate, meaning that these variables can be correlated, and it was also observed that each variable captures a different aspect of system performance that isn't fully redundant.

The results of the overall correlation analysis are that the correlations reflect the consistent picture of interconnections between important variables having been identified as key elements for sustainable crop production under climate-resilient management. There is a high positive correlation between the climate resilience index, the soil health index, and the sustainability performance index (SPI), indicating that extremely subtle but multi-dimensional measures are reflecting a common underlying dimension of system performance in relation to productive capacity and environmental quality of soil-based agroecosystems under stress. Important management-practice linkages with yield-related indicators also confirm that the climate-smart interventions assessed in the present project are effective in improving several aspects of agricultural sustainability

Principal Component Analysis

In order to better understand such a hidden structure of the multivariate data set and to define the latent factors that explained the variability in the systems' performance, principal component analysis (PCA) was applied to the correlation matrix of 62 variables, after standardization, measured on the 300 experimental plots. The dimensionality reduction technique resulted in the identification of fewer uncorrelated parts accounting for most of the variance in the original data, and it simplified the interpretation of the complex interrelationships between the soil properties, management practices, and crop performance indicators.

Three principle components with eigenvalues >1.0 were extracted by the PCA, representing a total variance of 82.4% in the data set. This shows a high value of cumulative explained variance, that is, the amount of information in the original variables accounted for by the three factor components is high, and that the PCA can be regarded as a valid method of data reduction. The first principal component (PC1) accounted for 38.7% of the variance with a positive value of soil organic carbon, available nitrogen, available phosphorus, available potassium, and soil health index. Since this was related to the central part of the soil properties that control the variation in the experimental plots, this component was interpreted as soil fertility and soil nutrient management. The soil organic carbon and available nutrients with high loading on PC1 are consistent with the regression results (Joshi et al., 2026), which show that soil organic carbon ranks the highest among the soil variables that were considered as predictors of the sustainability performance index.

The second principal component (PC2) contributed 27.5% of the variance and showed high positive values with indicators of water-use efficiency, climate resilience index, and use of drip irrigation and rainwater harvesting. This component was known as water management and climate resilience—strategies that maximize water use capacity and buffer the climatic variation—and was understood as this component. This highlights that PC2 is becoming a separate component of water management as one of the separated factors independent from soil fertility (Venot et al., 2017). The fact that the climate resilience index is positively loaded

on the said component is another indication about the conceptual hypotheses from the water management practices to the increased adaptive capacity.

The third principal component (PC3) accounted for 16.2% of the variance, in which some variables are highly ranked with positive values, including grain yield, biomass production, and crop productivity index, while other variables are moderately ranked with negative values, including pest incidence. This was interpreted as an indication of crop productivity and environmental sustainability related to the crop yield and in relation to the pest pressure. This negative loading of pest incidence on PC3 indicates that lower incidence of pests can be expected to be obtained from higher productivity plots, which is consistent with the correlation analysis that revealed that pest incidence is negatively correlated with climate resilience index (Sridhar et al., 2025). The demarcation of crop productivity as an independent variable from soil fertility and water management indicates yield may depend on other factors apart from soil and water, such as the dynamics of the various pests and crop genetic potential.

For easier interpretation, the varimax rotation was then used for the retained components in an attempt to maximize the loading of the variables on each component and to minimize the loading of variables on all of the components. The three components were still distinguishable, with the majority of the variables having high loadings on just one of the three components after rotation. The results were again consistent when finalized as a rotated component matrix, which aligned with the previous interpretation of the matrix: soil fertility dimension (PC1), water management dimension (PC2), and crop productivity dimension (PC3). The separation between the categories was a large one, indicating that the variables chosen did indeed differ in capturing various aspects of agroecosystems functioning and were not highly correlated; this allowed the various composite indices to be used to represent the functioning of the whole agroecosystem.

The PCA results give a simplified multivariate description of the complex data set in three components, which account for most of the variance in the data and which can be easily read. In accordance with the theoretical principles of climate-smart agriculture, focusing on the three dimensions of system performances—soil health, water conservation, and yield stability—as three key objectives, soil fertility, water management, and crop productivity were identified as the three most important factors of successful system performance. The importance of experimental design and the choice of the variable is further expressed by high cumulative explained variance (82.4%) obtained in order to confirm that the measured variables are the ones that explain the maximum possible sources of variation in sustainable crop production in the different agroecological settings.

The component loadings and variance common to each of the principal components are displayed in Table 3.

Table 3. Principal component analysis results showing component loadings, eigenvalues, and variance explained for the three retained components.

Variable	PC1 (Soil Fertility)	PC2 (Water Management)	PC3 (Crop Productivity)
Soil Organic Carbon	0.82	0.12	0.08
Available Nitrogen	0.78	0.15	0.11
Available Phosphorus	0.74	0.09	0.14
Available Potassium	0.71	0.13	0.10
Soil Health Index	0.85	0.11	0.06
Water-Use Efficiency	0.14	0.79	0.18
Climate Resilience Index	0.16	0.81	0.12
Drip Irrigation	0.08	0.76	0.09
Rainwater Harvesting	0.11	0.73	0.07
Grain Yield	0.13	0.16	0.80
Biomass Production	0.10	0.14	0.77
Crop Productivity Index	0.15	0.12	0.82
Pest Incidence	-0.09	-0.11	-0.65
Eigenvalue	4.64	3.30	1.94
Variance Explained (%)	38.7	27.5	16.2
Cumulative Variance (%)	38.7	66.2	82.4

The results of PCA agree with the regression and correlation results and are comprehensive for the multivariate structure of the experimental data. The regression analysis showed which are the predictors of the SP index, whereas the PCA showed the latent dimensions that describe the overall variation in all the measured indexes. The three components (soil fertility, water management, and productivity of the crops) represent three main but interconnected dimensions of the processes of climate-resilient agroecosystem management identified, which helps to design interventions that address soil fertility but also water management and productivity of the crops. The proportion of the variance accounted for by these components (82.4%) are relatively large, reflecting the experimental design and variable selection being able to include the principal sources of variance in sustainable crop production and thus give a firm foundation to the conclusions of this study.

Comparative Findings

All 20 agroecological zones were compared to a conventional farming system used as a control for the integrated climate-resilient treatments to put their performance in the context of agriculture at large. This comparative analysis is also used as a quantitative indicator to evaluate the relative benefit or advantage of implementing the climatically resilient practices and also as evidence for farmers and extension service/policy makers interested in shifting towards more climate-smart production systems.

From the comparative results, it was observed that the climate-resilient agroecosystem management practices performed better than the conventional agroecosystems in all the parameters assessed and always at the significant level in all the agroecosystems. The main indicator of agricultural productivity, grain yield, was enhanced by 29.4% with climate-resilient management, from an average of 3.2 Mg ha⁻¹ in the conventional plots to 4.1 Mg ha⁻¹ in the treated plots. The gain in yield was observed in all 20 agroecological zones, but the increase in yield is different in various zones, which range from 18.7% in semi-arid zones in which the inherent fertility of the sandy soil is low to 36.2% in humid tropical zones in which the inherent fertility of the soil is high. The consistency of the yield advantage provides support to the robust nature of the integrated strategies to boost productivity in the context of multiple environmental challenges while being resilient to climate change.

There was a 24.8% improvement in soil health, as measured by the composite soil health index, which incorporates soil organic carbon, available nitrogen, phosphorus and potassium, and soil pH, in soil under climate-resilient management compared to soil under conventional management. The integration of agroforestry with conservation agriculture (CA) showed the highest level of improvement with more carbon sequestration and nutrient cycling in both surface and subsurface soil (Joshi et al., 2026). The benefits of this improvement in soil health will be felt for the long term, with the more fertile soils reducing the need for external inputs and buffers to crop production to climatic shocks and thereby increasing the sustainability of the system.

A remarkable improvement in water-use efficiency was observed, from 8.2 kg/ha mm⁻¹ in conventional to 10.0 kg/ha mm⁻¹ in treated irrigation systems, which are major parameters for water-conserving management under water scarcity. The improvement was mainly due to the

use of drip irrigation and mulching, which minimized evaporative losses from the soil surface and focused water in the root zone of the crop (Venot et al., 2017). A similar contribution towards wind speed and canopy temperature reduction was observed for agroforestry treatments, helping to further reduce the evapotranspiration rates due to the presence of trees. This represents an increased efficiency of water use and is particularly relevant when considering the impact of climate change, as it demonstrates that the improved productivity of climate-resilient practices does not require any more water than the traditional practices.

Climate-resilient management resulted in 21.6% more water, nutrient, and energy inputs being utilized efficiently (resource use efficiency). The use of integrated nutrient management practices (IMNP) involving the use of organic farming inputs along with reduced doses of mineral fertilizers and the use of precision irrigation techniques that ensured the optimal delivery of water to the crop's demand played a major role in this improvement (Paramesh et al., 2023). The advantages of the more efficient use of the resources have economic and environmental implications, as the cheaper raw material is used and the nutrient flow is kept low and the accompanying water pollution is avoided.

Carbon sequestration potential from allometric equations of tree biomass for agroforestry practices and from the default IPCC method for soil carbon stock change was 18.5% higher in the case of climate-resilient management practices compared to conventional management practices. This was especially large for agroforestry systems, where another 0.8-1.2 Mg C ha⁻¹ yr⁻¹ came from biomass accumulation of trees in these systems. Conservation agriculture practices and mulching also contributed to sequestration of carbon through reduction of soil disturbance and organic matter content in the soil. Conservation agriculture practices and mulching also contributed to sequestration of carbon by reducing the soil's disturbance and increasing the organic matter in the soil, which in turn increases the soil's ability to be a carbon sink (Jose, 2009).

The performance of the climate-resilient system is compared with the conventional system in Table 4, which shows the percentage increase for each indicator.

Table 4. Comparative performance of climate-resilient agroecosystem management versus conventional farming systems across key indicators.

Indicator	Improvement (%)
Crop Yield	+29.4
Soil Health	+24.8
Water-Use Efficiency	+22.1
Resource-Use Efficiency	+21.6
Carbon Sequestration	+18.5

Comparative results demonstrate that the management strategies proposed for the agroecosystems under the climate scenario are evidently better in terms of different performance aspects as compared to conventional farming systems. The impact of these improvements was substantial and significant, ranging from 18.5% to 29.4%, and showed that

indeed, positive returns on productivity, soil health, water conservation, and resource use efficiency, as well as climate change mitigation, are possible for those producing through integrated climate change resilient practices. The findings are generalizable, as the country's advantages are consistent across 20 different agroecological zones, indicating the potential for transferring and adapting the strategies of climate-resilient practices and retaining the main climate-resilient aspects in any location.

The synergy between the climate-resilient interventions from this study is also highlighted in comparative analysis. Observed gains were not from one single practice but rather were a result of multiple practices that support and enhance each other to increase yield, improve soil health, optimize water use efficiency, enhance resource use efficiency, and reduce carbon sequestration. In conservation agriculture, for example, higher soil organic carbon was associated with higher water-holding capacity and nutrient availability and also led to higher yields with less irrigation and fertilizer. Agroforestry incorporation also contributed to the sequestration of carbon and provided the microclimate benefits that led to a better utilization of water and decreased the pest pressure. These effects can be called synergistic and require integrated management, rather than a series of management techniques.

The outcome of this comparative study is similar and did support the previous studies about climate-resilient agriculture. Such a yield increase observed here (29.4%) is comparable to the yield increase of 20-40% reported through the use of conservation agriculture and integrated nutrient management systems in the tropics (Hobbs et al., 2007). The soil health gain of 24.8% is comparable to long-term trials, which showed that soil organic carbon can be achieved at a rate of 0.3–0.6 Mg ha⁻¹ year⁻¹ through the use of organic amendments and no-till (Joshi et al., 2026). The efficiency of the water use of the drip irrigation system increased by 22.1%, which is in the range of 30–50% that is usually reported by drip irrigation systems (Venot et al., 2017). The increase in carbon sequestration potential (18.5%) is within the range estimated for agroforestry systems (0.5-2.0 Mg C ha⁻¹ yr⁻¹) by Jose (2009) depending on the tree density and species composition.

The comparative study also has some lessons for agriculture policy and practice. The significant and positive results in yield, soil health, water-use efficiency, resource-use efficiency, and carbon sequestration demonstrate that climate-resilient management can achieve several SDGs in concert, such as zero hunger (SDG 2), clean water and sanitation (SDG 6), responsible consumption and production (SDG 12), and climate action (SDG 13). The similarity of these benefits in different agroecological conditions indicates that the approaches are not environmentally specific and therefore could be readily scaled by policy incentives and through agricultural extension programs.

Discussion

Based on the outcomes of this multi-site field evaluation, the study provides strong empirical evidence that there can be no tradeoffs between improved productivity, environment, soil health, and water conservation, and that these four goals of improved agroecosystem management can be achieved together through a resilient approach to boosting productivity and conserving natural resources. The observed gain of 29.4% in grain yield, 24.8% in soil

organic carbon, and 22.1% in water-use efficiency shows that all of these goals can be synergistically realized by carefully designed farming systems.

designed management interventions. The results have important policy and practice implications in particular for agricultural systems under the stress of climate variability in the affected regions. The high value of the soil organic carbon ($\beta = 0.45$) and water use efficiency (WUE: $\beta = 0.39$) in the regression model suggests that SOC storage and WUE should be taken into consideration and measures that increase yield should be complemented with practices of conservation agriculture, mulching, and drip irrigation. In fact, as a practitioner, it's helpful that integrated nutrient management and climate-resilient crops emerged as a couple of key predictors for designing training and technology dissemination strategies to overcome a number of constraints.

The implications of this study for theory are not limited to the agronomic results but can also be applied to a general discussion of the design of sustainable agriculture systems. Empirical evidence of the agroecological approach set forth by Altieri et al. (2015), based on the incorporation of ecological principles into farming practices, was provided by PCA results, in which three dimensions were clearly identified: soil fertility, water management, and crop productivity, accounting for 82.4% of total variance. The high positive correlation between the climate resilience index and the crop productivity ($r = 0.84$) also shows that resilience and productivity are not mutually exclusive properties of well-functioning agroecosystems but can enhance each other. This finding has consequences for how agricultural sustainability is thought about beyond just maximizing yields but also considering aspects such as system stability, how well the system will adapt to shocks, and conservation of resources in the long term. The water management category was separated from the soil fertility category, indicating the need to include specific measures to address the water constraint, which is a significant constraint in the semi-arid and arid areas and which is likely to be exacerbated by climate change (Venot et al., 2017).

While the results are strong and reproducible across twenty agroecological zones, some methodological limitations should be considered when interpreting the results. The two seasons of the study period may not be enough to fully represent the dynamics of system responses to the climate-resilient management, especially for soil organic carbon change, which typically takes 5-10 years to reach a new equilibrium (Joshi et al., 2026). It is possible, though, that the observed 24.8% increase in SOC could be the beginning of a response that may either be amplified or capped at a higher level in the longer term. Additionally, although the experimental design was considered to be randomized complete block with three replications, the selection of some farms and farmers' fields may not well reflect the heterogeneity of the management system, the limitation of resources, and the socio-economic aspects of the smallholder farming systems. Data preprocessing to exclude observations from plots for which an observation was missing at the end of the planned observation period prior to a proper statistical analysis may also have produced a selection bias if missing observations were related to the type of response to the treatment or site factors. Furthermore, composite indicators, such as the sustainability performance index, can provide a broader evaluation of a comparison but can be influenced by the weighting and normalization of variables in the comparison, thus potentially altering the

relative ranking of the treatments. It is important to note that when interpreting such findings in the broader context of the literature concerning climate change and agriculture, it may be the positive, or null, studies that are more likely to be published than the negative studies.

This research has several avenues for further research that will enhance the knowledge base of climate-resilient agroecosystem management. The time scale of this study might not adequately represent the benefits, or potential problems, that the various soil management regimes might bring—or not—over a longer time horizon; there is a need for longer-term experiments—of several decades—to assess the temporal dynamics for soil carbon sequestration, nutrient cycling, and yield stability for the integrated soil management modalities. Future research should also address the socio-economic dimensions of adoption, including the labor requirements, input costs, and different risks associated with various climate-smart practices, which will play a crucial part in the decision-making of farmers and the interventions' scalability. Agroforestry integration has shown good results in improving carbon sequestration and regulation of microclimate; thus, further studies of optimal species selection, planting densities, and spatial designs of this practice for different agroecological zones would be useful to maximize the co-benefits of agroforestry. Finally, the interaction between the 10 strategies where they were used in this study should be further investigated by factorial experimentation that might be pursued to determine which combinations of strategies provide synergistic or antagonistic effects of multiple strategies. Further, belowground biodiversity, including soil microbial communities and the mycorrhizal network, which play important roles in nutrient cycling and plant health, has not been directly measured, and the effects of climate-resilient management have not been studied. Lastly, involvement of the farmer in designing and evaluating strategies for climate adaptation in the future research work is necessary because such local knowledge and adaptive management are important to define and to guarantee sustainability of the adaptation strategy as a function of the local socio-ecological situation.

Conclusion

This is a multi-site field evaluation to assess the potential to better sustainably crop production by implementing agroecosystem management strategies combined with a climate-resilient approach under the different agroecological contexts. We discovered in our study that many of the performance of agriculture outcomes are all optimized at once, and these strategies result in a 29.4, 24.8, and 22.1% higher grain yield, soil organic carbon, and water-use efficiency, respectively, compared with the conventional system. The model of regression by sustainable production allowed detecting 76.3% of the variance in the sustainable production, and soil organic carbon and water-use efficiency were the best predictor variables. Using PC analysis, we determined that soil fertility, water management, and productivity of the crops are three different yet complementary aspects of system performance. This revealed that agricultural productivity and environmental sustainability are not antagonistic but can be synergized through integrated agro-management systems to support the agro-ecological approach theoretically and provided empirical evidence to support the development of a climate-resilient agriculture system.

The findings of this work are important for agricultural policy and practice. These performance improvements are found in every one of the 20 agroecological zones and signal a positive trajectory for the introduction and dissemination of a package of conservation agriculture, integrated nutrient management, agroforestry, precision irrigation, and climate-resilient crops through extension and incentive packages. Long-term experiments (10 years and more) are required to ensure that the entire carbon cycle or system stability is taken into consideration, and participatory experiments that engage in studying the socio-economic impediments or otherwise to smallholder farmers' adoption should be adopted. Factorial designs—testing for interaction between different practices to enhance climate resilience—and testing multi-practice combinations on the impact to below-ground diversity would be beneficial to employ to strengthen the evidence base. Finally, this study provides evidence that the movement toward agroecosystems that are more resilient to climate change is not only needed to adapt to the growing threats from climate change but also can be an effective pathway for improving food security and soil health and reducing GHGs.

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