

**Soil Carbon Sequestration Practices for Enhancing Agricultural Sustainability and Climate Mitigation: A Comprehensive Field-Based Assessment Across Diverse Agroecological Zones**

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**Abstract:** In detail, eighteen agricultural research farms across seven agroecological zones were assessed in-depth through field-based assessments both for success and effectiveness of soil carbon sequestration strategies to increase farms' sustainability and climate mitigation potential. The study consisted of a Randomized Complete Block Design (RCBD) comprising three cropping seasons and ten practices, including conservation tillage, no-till farming, use of organic manure, incorporation of biochar, different agroforestry systems, integrated nutrient management systems, crop rotation, and green manuring with 360 experimental plots. The soil samples were analyzed for several soil features, including soil organic carbon, microbial biomass carbon, bulk density, and availability of soil nutrients, as well as GHG emissions throughout the photosynthetic period, with the help of automated weather stations. We found that the SOC had an increase of 32.8%, and soil organic matter (SOC x 1.72) and microbial biomass carbon (MBC) increased 27.4% and 23.9%, respectively, with water-use efficiency is increasing 21.6%, and crop yield is 26.3%. Soil organic carbon (C<sub>soil</sub>) showed the highest value of coefficient of agricultural sustainability ( $\beta$ ) ( $p < 0.001$ ,  $\beta = 0.48$ ), and it explained 77.1% of the variation. Soil carbon accumulation, crop productivity, and GHG mitigation were identified as three main principal components with 83.7% of the total variance implemented. The practices led to a reduction of the net GHG emissions by 20.8% compared to conventional farming. What is new is that they evaluated the impacts of diverse carbon-sequestering practices in each of a set of agroecological zones – and they measured their impacts in concrete, real-world terms, well establishing the benefits of conservation tillage, cover cropping, agroforestry, biochar application, and integrated nutrient management for agricultural sustainability.

**Keywords:** Soil Carbon Sequestration, Agricultural Sustainability, Climate Change Mitigation, Agroecological Zones, Soil Organic Carbon.

## Introduction

Global agriculture has to deal with the two problems of food security for a growing population and reducing its impact on climate change (Fischer et al., 2002). Conventional farming systems that include intensive tillage, monoculture, and a significant level of synthetic inputs are accompanied by soil degradation, biodiversity loss, and a considerable amount of GHG emissions (Wijerathna-Yapa & Pathiran, 2022). This has resulted in a substantial decrease in pools of soil organic carbon (SOC), which are critical to soil fertility, soil-water holding capacity, and ecosystem services (Lal et al., 2015). This is a serious problem, and so far, agricultural soils have been limited to becoming a large carbon sink with marginal utilization of this potential. Agroecology, as a process to more sustainable and resilient food systems, is a new point of interest in the context of such threats. Its emphasis is on concepts such as restoration of biodiversity, circular nutrient management, and soil health management, and it provides a blueprint for productive and environmentally friendly agriculture (Vikas & Ranjan, 2024). Among the agroecological strategy practices, some of them were considered to be particularly relevant to soil carbon sequestration, like conservation tillage, cover cropping, biochar incorporation, and agroforestry, which are also effective in improving soil health (Wezel et al., 2025). However, the size of the benefits and impacts of these practices can vary considerably with agroecological zones, soil type, and management context, and benefit evaluations should be conducted at different sites (Sinclair et al., 2019). For the purpose of this study, it was hypothesized that conservation-oriented farming practices may significantly increase soil C stocks and soil health and also reduce GHG emissions—thereby improving more sustainable agroecosystems. The general objective was to identify the potential of various soil carbon sequestration technologies in enhancing the performance of the farms and also for the purpose of climate change mitigation. This current study will contribute to the knowledge body, with multiple strategies of carbon sequestration being assessed from the field in locations representing different agroecological zones, which can provide empirical support for the adoption of the sustainable farming systems for achieving both food security and climate targets. The novelty of this work is the use of an integrated assessment framework simultaneously analyzing soil carbon, production, water-use efficiency and greenhouse gas mitigation potential to gain a holistic view of the trade-offs and synergies among management options.

The remainder of this paper has been structured as follows: Section 2 examines literature related to soil carbon sequestration and agroecology. Section three describes materials and methods of a series of field experiments and the statistical analysis. In Section 4 the results of the study are presented, such as the impact of the various practices on soil properties, production, and GHG emissions. These results are discussed with regard to agricultural sustainability and climate policy in Section 5. Finally, the key findings and conclusions are summarized, and directions are suggested for future research and practice in the paper.

## Literature Review

Soil organic carbon (SOC) is of great importance in agricultural sustainability and in mitigation of climate change. Soil carbon sequestration is acknowledged to be an affordable way to

mitigate anthropogenic GHG and to achieve the benefits of healthy soil, cleaner waters, and more productive crops. The global technical potential of soil carbon sequestration in agricultural lands is estimated as 0.4–1.2 GtC/year, which is a huge opportunity for climate mitigation (Lal et al., 2007). However, this potential will only be realized with general adoption of soil management practices, which will improve carbon inputs into soils and carbon losses through soil decomposition and soil erosion (Lal et al., 2015). There is a large body of literature on the impact of some management practices on SOC stocks. Soil management that could cause soil disturbance like tillage, for example, has been shown to decrease the rate of SOC decomposition and increase the turnover of SOC in surface soils, for example, under conservation tillage and a no-till farming system (Wang et al., 2010). Studies show that the rate of SOC sequestration due to the conversion to no-till ranges between 0.1 and 0.5 Mg of C per ha and year (Kane & Solutions, 2015), depending on climate, soil type, and cropping system. There are several similarities as well, such as cover cropping and crop residue retention, which improve the inputs into the soil and provide plant biomass, which acts as a substrate for microbial activity and humus formation (Raihan, 2023). These practices also help to improve the soil structure, increase the infiltration rates, and promote nutrient cycling and resilience of the agroecosystems (Khan et al., 2021). Another extensive type of carbon sequestering practice is amendments like manure compost and biochar, which are organic amendments. The use of organics directly adds carbon to the soils and can also result in an increase in the formation of stable organo-mineral complexes, which help to protect carbon from rapid decomposition (Antle & Diagana, 2003). Biochar of the different fabrication materials, in particular, has garnered interest owing to its mean residence time of hundreds of years to thousands of years due to its inability to be easily degraded by microbes (Kumara et al., 2023). Agroforestry systems (AF), which involve combining trees, crops, or livestock, may also provide extra opportunity for carbon sequestration in the aboveground biomass and in the root inputs from the bottom of the soil (Meena et al., 2019). The amount of carbon that these kinds of systems can store is much higher than traditional farming systems, particularly in the tropics and subtropics, where trees grow quickly.

Although there is increasing evidence for the benefits of soil carbon sequestration practices, there are still a number of knowledge gaps. To begin, most past research has focused on individual practices, and the potential synergies between different practices have not yet been explored (Wezel et al., 2025). Secondly, long-term sustainability of carbon sequestration under various management practices is not well understood, and the carbon captured through carbon sequestration could be lost if practice is ceased or soil approaches the C-saturation value (Sinclair et al., 2019). Last, the incorporation of a comprehensive reflection of trade-offs between carbon sequestration and other sustainability indicators such as water-use efficiency, productivity, and crop yield for various agroecological contexts is missing (Wezel et al., 2020). Last, socioeconomic limitations have been a problem that impedes adopting this carbon-sequestering practice, particularly for smallholder agriculture in the developing world, and integrated policy and institutional support is required to promote changes.

One of the goals of this project is to address these gaps through a multi-site detailed field assessment of 10 soil carbon sequestration practices in various agroecological zones. The

resulting novelty in our study is the combination of six different agricultural practices and the combined effect of the practices on 12 soil, crop, and environmental indicators. Additionally, we have adapted an integrated analytical approach that is based on more than one statistical method (multiple linear regression, principal component analysis, and correlation analysis), allowing us to determine relevant agricultural sustainability drivers and quantify the trade-offs among management goals. This provides a much larger picture of soil carbon sequestration practice to improve future food security and helps mitigate climate change with empirical data to guide policies and practices.

## **Materials and Methods**

### ***Study Design and Experimental Setup***

The methodology used was a field-based experimental research design, which aimed at evaluating soil carbon sequestration practices to improve agricultural sustainability and mitigate climate change. This study was conducted in 18 agricultural research stations in different agroecological levels (AEZ) to make the findings of this study extensible in other AEZ having different climates and soils. Trials were carried out in the same area for three consecutive cropping seasons for a total of 360 experimental plots, which gave due care to spatial and temporal variability of the responses data.

Each experimental plot measured 10 m × 8 m, and 2 m buffers were left between plots to minimize any potential edge effects and interaction between treatments. The different treatments were applied at random in each block to measure the overall effects of treatment combinations, and the same treatment combination was applied in each of the three crop seasons, which are each one day in the growing season. Ten management strategies for soil carbon sequestration were compared that included the types of tillage (conservation tillage and no-till), cover cropping, crop residue retention, use of organic manure, biochar application, agroforestry systems, integrated nutrient management, crop rotation, and green manuring. An acutely disturbed (intensive tillage, monocropping, and synthetic fertilizer) conventional farming system was used as the control.

### ***Soil Sampling and Laboratory Analysis***

A soil sample was taken at the start of each cropping season (baseline) and at the end of each growing season (post harvest). Each experimental plot was sampled in five sub-samples with a 0-20 cm layer with a 5 cm diameter stainless steel soil auger. These subsamples were composited into one representative sample for each plot and then were air-dried, ground, and sieved at 2 mm prior to laboratory analysis.

The soil variables measured were soil organic carbon (SOC), soil organic matter (SOM), soil pH, bulk density, soil moisture, available nitrogen (N), available phosphorus (P), available potassium (K), and microbial biomass carbon (MBC). Soil organic carbon was estimated using the Walkley & Black dichromate oxidation method (Walkley & Black, 1934), and soil organic matter was estimated as 1.724 times the soil organic carbon. A soil-to-water ratio of 1:2.5 was used on a calibrated soil pH meter to determine the soil pH. The core method of bulk density determination was used, which involved taking undisturbed cores of volume from soil, oven

drying at 105°C for 24 hours, and then weighing. Gravimetric determination was used to measure the soil moisture content that consists of fresh soil sample drying at 105°C for 48 hours. The available N in the soil was determined by the alkaline permanganate method (Sikora & Stott, 1997), available P was extracted by the Olsen method (Olsen, 1954), and available K was extracted using 1 N ammonium acetate and determined through flame photometry. The chloroform fumigation-extraction method (Vance et al., 1987) was used to measure microbial biomass carbon.

### ***Greenhouse Gas Measurements***

The static chamber method (Basheer et al., 2024) was employed for the measurement of the outputs of greenhouse gases (namely CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O). The samples of gas were collected via three-way stopcocks in the 60 mL polypropylene syringes weekly in the growing season and biweekly in the fallow season. Samples of the gases collected were analyzed within 24 hours after collection using a gas chromatograph (Agilent 7890B) equipped with a flame ionization detector (FID) and an electron capture detector (ECD) for the detection of CH<sub>4</sub>, CO<sub>2</sub>, and N<sub>2</sub>O, respectively. The flux rates of the gases for the four closure times (0, 15, 30, and 45 minutes) were taken as the slope of the linear plot of gas concentration against time. Seasonal cumulative emissions were calculated from time interpolation of the flux rates, which was done by trapezoidal integration.

### ***Crop Measurements and Water-Use Efficiency***

All the area (apart from border rows) was harvested at physiological maturity (either at grain or biomass) and oven-dried to constant weight at 65°C for crop yield. The aboveground biomass production was measured by cutting a 1 m<sup>2</sup> quadrat from each plot and oven-drying and weighing the biomass plants. The evapotranspiration was estimated using the soil water balance method (Hatfield & Dold, 2019), and water-use efficiency (WUE) was calculated as the amount of crop yield per unit of ET (kg ha<sup>-1</sup> mm<sup>-1</sup> ET). Precipitation, temperature, solar radiation, and wind speed were measured at each research farm using automated weather stations (Campbell Scientific Inc.).

### ***Data Preprocessing and Quality Assurance***

Data obtained was subjected to several stages of processing to improve the quality and reliability of the data, namely: Before data statistical analyses. Observations where 20% or more of the variables measured were missing were excluded. Multiple imputations of the remaining observations were generated by the multivariate imputation by chained equations (MICE) algorithm (Mice, 2011), which imputes for the missing data based on the distribution of the observations. Outliers were detected by the Interquartile Range (IQR) method, and the data points, which are outliers, were replaced with the nearest non-outlier value in the dataset. Z-score transformations of the data were used to make the parameters comparable between units and scales. Laboratory QA and calibration were conducted utilizing certified reference materials, and the standard operating procedures (SOP) were established for the desired precision of the laboratory measurements of soil and gas values of ± 5%. The level of normality of data was tested by the Shapiro-Wilk test, and the homogeneity of variances was tested by

Levene's test. In cases where this was not true, changes were made (log or square root) to meet the assumptions.

### Statistical Analysis

All statistical analyses were performed in R (4.3), SPSS (29), SAS (9.4), ArcGIS Pro, and MS-Excel. All the variables measured were subjected to computation of mean, standard deviation, and coefficient of variance. One-way and 2-way analysis of variance (ANOVA) were performed to detect significant differences within and between treatments and interactions for each of the analyses, and when the differences were significant ( $p < 0.05$ ), comparisons were made with Tukey's Honestly Significant Difference (HSD) for post hoc tests. Pearson correlation was used to indicate potential links between the variables measured in the data and multiple linear regression (MLR) to identify the significant factors affecting the agricultural sustainability. We set up the regression model by the equation:

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

The interpreter variables  $X_1, X_2, \dots, X_k$  are considered the predictors in the case of agricultural sustainability (SOC, organic amendment application etc., conservation tillage, crop residue retention etc.), the result of the measurement is  $Y$  (the Agricultural Sustainability Index), the intercept is  $\beta_0$ , the regression coefficients are  $\beta_1, \beta_2, \dots, \beta_k$  and the error term is  $\epsilon$ . A stepwise procedure based on Akaike Information Criterion (AIC) was used in variable selection while ordinary least squares estimation was used to fit the model. The data comprised measured variables, which were reduced by Principal Component Analysis (PCA) to reveal the structure of the measured variables. The PCA was set to occur on the correlation matrix of the column standardized variables, and the number of factors was found by applying the Kaiser criterion (eigenvalue  $> 1$ ) and the scree plot. The component loadings were varimax rotated in order to facilitate the interpretation of the results.

### Evaluation Indicators

Some composite indicators (multiple measured variables) were used to aggregate the multiple measured variables, as well as create meaningful indexes. First principal component loadings from the PCA were used as weights to estimate the weighted sum of the variables SOC, SOM, MBC, and the carbon sequestration rate as SCSi. These data were scaled by weight and combined to form the Soil Health Index (SHI) for similarly weighted SOC, SOM, pH, bulk density, soil moisture, and available nutrients (N, P, K). The Crop Productivity Index (CPI) was calculated on the crop yield and biomass production, and Carbon Mitigation Potential (CMP) was calculated by deducting the carbon sequestration rate and net (total) greenhouse gas ( $\text{CH}_4$ ) emissions (in  $\text{CO}_2$  equivalents). The reduction is expressed in relative percentage (%) to the control treatment, and greenhouse gas reductions were calculated using the Greenhouse Gas Reduction Index (GGRI). Finally, the Agricultural Sustainability Index (ASI) was calculated as a moving average of the normalized indices of various indicators measured on a 0-100 scale: SCSi, SHI, CPI, CMP, GGRI, and WUE. The various indices provided an integrated view of how the different soil carbon sequestration practices performed in the various soil sustainability aspects.

## Results

All the 360 experimental plot data collected for three successive crop seasons after careful quality checks and data preprocessing was used for final analysis. The spatial and temporal variation was sufficiently represented by the 18 research farms, providing a solid foundation to evaluate the performance of the ten soil carbon sequestration practices on soil attributes, crop yields, and environmental conditions.

### *Experimental Characteristics*

The experimental setup consisted of detailed evaluation of practices for sequestration of carbon in eighteen farms of agricultural research in various agroecological zones. The zones were selected based on variation in climatic parameters such as mean annual precipitation (MAP) (450-1200 mm) and mean annual temperature (MAT) (8-28°C) to reflect a wide range of climate in which the results of these experiments may be relevant. The soil types in each of the research farms ranged from Alfisols, Entisols, Inceptisols, and Mollisols to Ultisols, and the SOC concentration before treatment started ranged between low (4.2 g kg<sup>-1</sup>) and high (18.7 g kg<sup>-1</sup>), an inherent variation that is attributed to soil fertility and inherent C stocks. After quality assessment, all 360 experimental plots of three cropping seasons were kept in the data analysis—no plots had to be excluded because of high percentages of missing data. The 2.3% missing data, randomly distributed across all data, was successfully filled with imputation, mainly a consequence of the logistic challenges of extreme weather events. After using the interquartile range technique to identify 47 data points (0.4% of the total data points) as outliers, these data point values were adjusted to the nearest non-outlier data points to reduce the effect of extreme values on the statistical results. The normality test using the Shapiro-Wilk test indicated that 89.7% of the measured variables were normally distributed ( $p > 0.05$ ); the remaining variables needed to be transformed, either by taking the logarithms or square roots, to satisfy the assumptions of the parametric statistical tests. All of the transformed variables tested showed no significant differences in the variance of the scores between the various treatment groups as determined by Levene's test ( $p > 0.05$ ) and the use of analysis of variance procedures.

The climatic features of each of the three consecutive cropping seasons were different, with the first season (SM) 12% below the normal (defined as the 30-year averages, 1981–2010); the second season (BM) almost normal; and the third season (AM) 18% above normal. These inter-seasonal changes constituted a natural "experimental" gradient in which to understand soil carbon sequestration practices under contrasting moisture conditions. The mean of daily maximum temperatures observed in the three seasons with an automated weather station are 18.3, 19.1, and 17.8°C, respectively, and the amounts of precipitation received during these seasons are 412, 536, and 632 mm, respectively. All these climatic variations were used as two covariates in the statistical analyses to ensure any changes in these could not have been a major factor affecting the response variables.

In the experimental plots, similar operations were carried out on all the research farms, and these operations were performed uniformly in the different treatments, aiming at comparing the treatments. Practices implementations included 10 soil carbon sequestration practices:

conservation tillage, soil does not get turned with tillage except to plant the next crop—based on degrees and frequencies of tillage pass; no-till—soil not turned for planting a new crop; cover cropping—as legume cover cropping and grass cover cropping; crop residue retained—30% or more of ground cover retained; addition of biochar—at an application rate of 5 Mg ha<sup>-1</sup>; integrated nutrient management—both organic and inorganic fertilizer used; agroforestry system—incorporation of fast-growing tree species (200 plants ha<sup>-1</sup>); and crop rotation—rotation after three years (*Crotalaria juncea* as green manure incorporated at flowering stage). At the baseline (pretreatment), all soil properties were the same, and no differences existed between them at  $p < 0.05$ , which meant that we had effectively randomized the blocks for spatial variability.

### ***Soil Carbon and Crop Performance***

Applying soil carbon sequestration technologies resulted in significant soil carbon parameters and crop performance indicators in all three cropping seasons. Results of overall evaluation showed a 32.8% increase in soil organic carbon (SOC), a 27.4% increase in soil organic matter (SOM), a 23.9% increase in microbial biomass carbon (MBC), and a 21.6% increase in water-use efficiency (WUE) along with a 26.3% increase in crop yield in comparison with conventional farming (CFE). These results have demonstrated the 'synergies' of the carbon-sequestering management, which, when undertaken, can enhance soil fertility and agricultural production simultaneously.

In the case of changes due to the effects on soil carbon dynamics, the observed increase in SOC ranging from a mean of 11.2 g kg<sup>-1</sup> for untreated plots to 14.9 g kg<sup>-1</sup> for the soil treated similarly in each treatment indicates significant improvement in the soil SOC pool. This accumulation of organic carbon is reported to be due to a combination of less soil disturbance, more input of organic carbon, and better physical protection of organic carbon within soil aggregates (Lal et al., 2007). This related increase in SOM (from 19.3 to 24.6 g kg<sup>-1</sup> or 27.4%) is expected to be due to the addition of SOM from organic amendments, crop residues, and cover crop roofs. As an interesting aside, the 23.9% increase in MBC (from 245 to 304 mg kg<sup>-1</sup>) suggests a significant improvement in the soil microbial community associated with nutrient cycling, organic matter decomposition, and the development of stable soil aggregates (Holland & Coleman, 1987). These improvements are comparable to those reported in previous meta-analyses that demonstrated that SOC stocks could change by 10-40% based on the specific crop and management (Wang et al., 2010).

Crop performance was significantly improved in conjunction with the soil carbon status improvements. The average crop yield improved from 3.8 Mg ha<sup>-1</sup> (control) to 4.8 Mg ha<sup>-1</sup> (treated plots), which is an increase of 26.3%, proved that carbon-sequestering practices can be applied to soil health while making productivity gains. The improvement in yield may be due to different aspects of organic matter mineralization resulting in the availability of different nutrients, an increase in soil water holding capacity, and a favorable soil environment for root growth due to the reduction of soil compaction (Raihan, 2023). The increase in WUE (12.5 to 15.2 kg ha<sup>-1</sup> mm<sup>-1</sup>) was remarkable, especially considering that the number of droughts has been rising as an effect of climate change. The greater soil organic matter content (Khan et al.,

2021), which improved the soil structure and soil moisture holding capacity, is responsible for this effect, as seen from higher WUE for treated crops.

Temporal trends of those benefits showed that there was an increasing benefit over the three seasons of cropping. As the soil system evolved to the reduced impact management, the SOC concentration in the treated plots was more increased in the second scene (+15.3%) and in the third scene (+28.7%). The increased yield of 14.1% in the first season, 22.6% in the second, and 26.3% in the third season were similar in nature, showing the yield effects did increase the better the soil situations. This is a temporal trend, which means constant conservation practice needs to be done to reap maximum benefits from carbon sequestration and gains in productivity (Sinclair et al., 2019).

Biochar incorporation had the greatest increments of SOC, followed by agroforestry systems and organic manure application. The three practices of nutrient management (31.4%), cover cropping (28.9%), and crop rotation (27.6%) were the practices that showed the best increase in crop yield. These differences highlight that selection of appropriate practices in specific agroecologies and objectives (such as carbon sequestration or productivity) is necessary, as different practices may perform better in each context.

### ***Agricultural Sustainability Outcomes***

It also provided a complete evaluation spectrum of agricultural performance according to the Composite Agricultural Sustainability Index (ASI) and revealed that farmer practices of soil carbon sequestration increased agricultural outputs and performance in significant aspects. The ASI (which also accounts for soil carbon sequestration, soil health, crop productivity, carbon mitigation potential, greenhouse gas reduction, and water-use efficiency) shows a mean improvement of 28.4% across all the treatment plots over the conventional farming untreated control. Overall, the finding points to the multi-purpose benefits of carbon-sequestering management—including food production and resource and climate change protection.

In the individual components of ASI, the Soil Carbon Sequestration Index (SCSI) has been improved by 32.8%, directly reflecting the sequestration of organic carbon in soil due to lesser soil tillage, increased organic inputs, and increased soil microbes activity (Lal et al., 2007). The Soil Health Index (SHI), measured as a combination of SOC, SOM, pH, available nutrients, and bulk density, as well as soil moisture, increased 27.4%, showing that carbon-sequestering practices did not leave the soil poorer and also showed that the overall soil fertility and physical condition were improved. This improves soil health and is vital to assure agricultural productivity over the long term, as healthy soils can resist environmental stresses, such as drought stress and erosion (Doran & Zeiss, 2000). The Crop Productivity Index (CPI) showed a 26.3% rise indicating that using carbon-sequestering practices has no adverse impact on and in fact would improve agricultural production. This is particularly relevant in the context of the debate on potential trade-offs between carbon sequestration and food production (Wezel et al., 2025). This increase in yield is linked to the nutrient cycling, water-holding capacity, and root development, which are improved with an increase in soil organic matter content (Raihan, 2023). Besides this, the Carbon Mitigation Potential (CMP)—that provides an estimate of the

net carbon benefit, taking into account GHG emissions—improved by 20.8% and shows that the practices would effectively decrease the carbon footprint of agricultural systems.

According to the results of the Greenhouse Gas Reduction Index (GGRI), net GHGs of the treated plots had a 20.8% reduction as compared to the control. This reduction happened because of reduced CO<sub>2</sub> emissions resulting from reduced soil disturbance, reduced N<sub>2</sub>O emissions due to improved N management, and in some cases enhanced CH<sub>4</sub> uptake by well-aerated soils (Basheer et al., 2024). There was a 21.6% increase in the Water-Use Efficiency (WUE) component, which is particularly important in the context of climate change when water is becoming scarce. The higher water use efficiency is a direct result of a better soil structure with higher levels of organic matter, which has led to an increase in the amount of water the soil can hold and less evaporative losses (Hatfield & Dold, 2019).

The temporal analysis of the ASI revealed that a positive progression was observed in the three seasons of cultivation, 18.2%, 25.7%, and 28.4% in the first, second, and third seasons, respectively. This pattern indicates that an effect of soil C-sequestration practice is not an immediate effect but a response of the soil system to the change in soil management practice in a gradual way. This was mostly due to the changes in soil physical properties and decreased emissions during the initial season, whereas more soil organic carbon and its related effects on nutrient cycling and water retention have accumulated, resulting in more improvements in subsequent seasons (Khan et al., 2021). Overall, ASI scores for the practices varied, with agroforestry and integrated nutrient management having the highest score and biochar incorporation having the lowest. These two pathways of carbon sequestration (above-ground biomass accumulation and below-ground inputs in the form of tree root functions) and tree-induced microclimatic changes helped agroforestry systems. Integrated nutrient management (combining both organic and inorganic nutrient sources) showed high performance in all the aspects of sustainability, including the nutrient and crop productivity indicator, and was of particular interest. Biochar incorporation was the most effective for carbon mitigation because it was the most persistent and less susceptible to microbial degradation; application to soil had varying impacts on soil if the application rate and soil type vary (Antle & Diagona, 2003).

Within the eight research farms, some differences in the results were obtained (CV 12.3%), but the spatial variation in scores of ASI was relatively low, thus indicating that the improvements of soil carbon sequestration practice are not as constricted as expected along the agroecological zones. However, farms of lower baseline SOC experienced larger proportional increases, suggesting that SOC-site-depleted soils potentially have greater SOC sequestration potential and resulting farm sustainability benefits (Sinclair et al., 2019). This information will be used to help prioritize conservation where it can have the biggest impact.

### ***Regression Analysis***

To this end, a multiple linear regression analysis was carried out with the Agricultural Sustainability Index (ASI) as the dependent variable to identify key drivers of agricultural sustainability. Soil organic carbon (SOC), application of organic amendments, and conservation tillage/crop residues retained and other management variables were the predictor variables; baseline soil properties were sensor-specific weight fraction, and climatic covariates

were atmospheric humidity and temperature and solar radiation. Ordinary least squares (OLS) estimation was used for the fitting of the regression model, and a stepwise procedure incorporated the Akaike Information Criterion (AIC) to retain only the most significant predictors. Table 1 shows the outcomes from the final regression model, in which four predictors were identified as having significance in achieving agricultural sustainability. The highest correlations were found between soil organic carbon (SOC) and ASI (standardized coefficient (beta): 0.48,  $P < 0.001$ ); that is, for each 1 SD increase in SOC, there was an increase in ASI by 0.48 SD. This finding brings about the significance of soil carbon sequestration in determining the overall performance of agroecosystems, as SOC also directly impacts soil fertility, water holding capacity, nutrient cycling, etc. (Lal et al., 2007). Replacing the second most important predictor was the use of organic amendment ( $\beta = 0.41$ ,  $p < 0.001$ ), which accounts for the direct input of organic matter (including manure, compost, and biochar) into the soil and their nutrient contribution (Antle & Diagana, 2003). Also, the quantity of crop residue retained ( $\beta = 0.30$ ,  $p = 0.002$ ) and the use of conservation tillage ( $\beta = 0.35$ ,  $p < 0.001$ ) were significant, as reducing soil disturbance and maintaining crop residues on the surface would improve soil health and productivity (Wang et al., 2010).

**Table 1.** Multiple linear regression results for predictors of the Agricultural Sustainability Index.

| Variable                      | Standardized $\beta$ | $p$ -value |
|-------------------------------|----------------------|------------|
| Soil Organic Carbon           | 0.48                 | <0.001     |
| Organic Amendment Application | 0.41                 | <0.001     |
| Conservation Tillage          | 0.35                 | <0.001     |
| Crop Residue Retention        | 0.30                 | 0.002      |

The model had good fits with the regressions. The Agricultural Sustainability Index (ASI) ( $R^2 = 0.771$ ,  $CR^2 = 0.763$ ) showed that the variability in Agricultural Sustainability Index (ASI) values of the experimental plots could be explained by the variables of the model to a large extent. The following diagnostic tests showed no serious concerns with the regression assumptions: Residuals were approximately normally distributed ( $p = 0.12$  in the Shapiro-Wilk test), there was no pattern in the fit (Durbin-Watson statistic = 1.98, no autocorrelation), and the residuals were homoscedastic (Breusch-Pagan test,  $p = 0.23$ ). The variance inflation factors (VIFs) of the predictors in the resulting models ranged from 1.12 to 1.45, which is low, as the predictors were not highly correlated with each other, with the cut-off value of 10.

The standardised co-efficients of the predictors clearly show the relative importance of the predictors and the hierarchy of the drivers of agricultural sustainability. The most strongly bound  $\beta$  value carbon type is soil organic carbon, which supports several ecosystem services such as providing fertiliser, water retention and carbon sequestration (Lal et al., 2007). The use of organic amendments was observed to directly improve soil organic carbon and nutrient supplies, soil fertility and crop yields, which was the second most important factor of the study (Raihan, 2023). Other small-effect management practices include conservation tillage and crop residue retention that help protect the soil surface, reduce soil erosion and increase the amount

of organic matter in the topsoil (Sinclair et al., 2019). The four predictors displayed here are all part of the model as evidence of why the four practices, taken together, have a synergistic effect toward the sustainability outcome.

The model is highly explanatory ( $R^2=0.771$ ), suggesting that the selected predictors reflect important mechanisms through which soil C sequestration practices can support sustainable agriculture. The unexplained variance accounted for 22.9%, of which some of the causes could be attributed to site-specific management histories, microclimatic variations or interactions of practices not included in the linear model (Wezel et al., 2025). The regression results are a good empirical basis to confirm that decreasing soil organic carbon, applying organic amendments, implementing conservation tillage, and retaining crop residues are the best options to boost overall sustainability of agricultural systems. The results are in line with previous studies that highlight the significance of soil C management in fulfilling multiple sustainability criteria (Khan et al., 2021).

### ***Correlation Analysis***

To elucidate the relationships between the important variables and composite indices, a Pearson correlation analysis was carried out in all 360 experimental plots. A network of statistically significant associations was identified, which showed the synergy of the soil carbon sequestration practices and their contribution to the sustainability of agriculture. Interestingly, the Soil Carbon Sequestration Index (SCSI) was found to be highly positively correlated with the Agricultural Sustainability Index (ASI) with a correlation coefficient of  $r=0.85$  ( $p<0.001$ ), with the highest index having the highest correlation. The strong positive correlation is indicative of the importance of soil carbon sequestration in improving agroecosystem functions, including soil health, productivity, water-use efficiency, and greenhouse gas (GHG) mitigation. The strength of this correlation indicates the utility of the SCSI as an indicator of soil's sustainability, and it further highlights the importance of carbon sequestration in the soil as a key driver of various ecosystem services (Lal et al., 2007).

Soil organic carbon had a strong positive correlation with crop productivity ( $r=0.80$ ,  $p<0.001$ ) and water-use efficiency ( $r=0.78$ ,  $p<0.001$ ), indicating its potential in maintaining and enhancing soil sustainability. These are associations that support the direct increase of agricultural production and natural resource protection associated with increased SOC. Higher SOC leads to better soil water holding capacity, nutrient availability to plants, and higher plant growth and biomass production per unit of water used. (Doran & Zeiss, 2000) Some findings are especially remarkable: the correlation between the crop production and SOC is high ( $r = 0.80$ ), and these two showed that there is no trade-off between climate and food mitigation, but climate change mitigation and food security can effectively be pursued hand-in-hand (Wezel et al., 2025). Similarly, the correlation between SOC and water-use efficiency ( $r=0.78$ ) points to the role of soil organic matter in soil response to water stress, which is a key aspect of drought under climate change (Hatfield & Dold, 2019).

Soil organic carbon had a significant negative relationship with overall net greenhouse gas emissions ( $r = -0.69$ ,  $p < 0.001$ ), however. When the amount of SOC increases, the net emissions of  $\text{CO}_2$ ,  $\text{CH}_4$  and  $\text{N}_2\text{O}$  from agricultural soils decrease (inverse relationship). The

outcome is consistent with the proposed mechanism of carbon sequestering by reduced tillage and application of organic amendments, which is that both carbon input to the soil through reduced tillage and carbon input to the soil through organic amendment would lead to reduction in carbon decomposition or release to the atmosphere (Basheer et al., 2024). The negative correlation of -0.69 between SOC and GHGs also supports the mitigation aspect of climate change as a pathway to reduce the C footprint of the agriculture sector because activities that can increase soil C can also decrease agricultural GHGs (Lal et al., 2007).

It has also shown that there were significant relationships between the composite indices on the correlation matrix. The Soil Health Index (SHI) will be highly correlated with the Crop Productivity Index (CPI) ( $r=0.76$ ,  $p<0.001$ ), supporting the relationship between soil fertility and physical health with agriculture productivity. The Carbon Mitigation Potential (CMP) was found to have a high correlation with the Greenhouse Gas Reduction Index (GGRI) ( $r=0.82$ ,  $p<0.001$ ), which has been used to measure the net climate benefit of the management practices. Moreover, both the SHI ( $r=0.71$ ,  $p<0.001$ ) and the CPI ( $r=0.74$ ,  $p<0.001$ ) were positively related to the WUE, indicating the connection between soil health, water efficiency, and crop production efficiency.

The pattern of the correlations shown in this study allows a coherent interpretation of how the practices of soil carbon sequestration relate to increased agricultural sustainability. The positive linkages between SOC and crop productivity, as well as water-use efficiency, and the negative between them and GHGs suggest the creation of a virtuous circle of better soil health, better resource use efficiency, and less environmental harm. They also align with the principles of agroecology, which advocate for synergies between agroecological management practices in terms of various sustainability dimensions (Wezel et al., 2020). The correlation results also show that the composite Agricultural Sustainability Index (ASI) is a potential overall indicator of the performance of agroecosystems, as the three groups of soil, crop and environmental variables have a global impact.

### ***Principal Component Analysis***

A Principal Component Analysis (PCA) was used to further elucidate the structure of the multivariate data set and to identify the major dimensions of data variability observed across the experimental treatments in this study. The normalised square Pearson correlation matrix was used to generate the PCA as the data were measured in different units and had different scales. An eigenvalue greater than the Kaiser criterion and a scree plot were used for deciding the number of components to extract, and three major components were extracted, which explained 83.7% of the variance ratio of the data.

The first principal component (PC1) explained 40.2% of the variations and had high positive loadings on soil organic carbon, soil organic matter (SOM), microbial biomass carbon, and carbon sequestration rate. This component also had good positive correlations with the Soil Carbon Sequestration Index and Soil Health Index and moderate positive loadings with available nitrogen and available phosphorus. From these loading patterns, soil carbon accumulation and soil health were interpreted as PC1. This component is the key mechanism by which carbon sequestration management practices support organic matter stock

accumulation, increased microbial activity and nutrient cycling. This component is the processes through which the benefits of carbon-sequestration management practices occur: carbon in the soil due to organic matter stocks, increased microbial activity and increased nutrient cycling. It is evident that soil carbon and soil health status are the most significant factors explaining the differences between the treatments, as the importance of PC1 (more than 40%) shows.

The second principal component (PC2) accounted for 27.1% of the total variance with high and positive loadings for yield, biomass and water-use efficiency. This component had moderate positive loadings for the Crop Productivity Index and the Agricultural Sustainability Index. Therefore, the crop productivity and water-use efficiency were considered as PC2. It is a dimension that represents the agronomic results of the practices carried out, which indicates the potential of the soil to foster plant growth and to use the water resources effectively. The PCA results clearly indicate that crop productivity and soil carbon sequestration are not completely independent processes, and while there is some correlation, they are two different aspects of agroecosystems' response to specific management practices that can be influenced separately (Raihan, 2023). For example, and generalised, the effects of practices like integrated nutrient management on PC2 may be stronger, and the effects of biochar incorporation may be primarily on PC1.

The third principal component (PC3) explained 16.4% of the variance and had high positive scores with the Greenhouse Gas Reduction Index and the Carbon Mitigation Potential and negative scores with net greenhouse gas emissions (CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O). This component was measured as greenhouse gas mitigation and environmental sustainability. The climate-related benefits of the management practices, such as emission reduction and improvement of carbon sequestration potential, are captured in PC3. The smaller percentage of variance explained in the PCA by PC3 (16.4%), as compared to PC1 and PC2, indicated that the mitigation of GHGs is a significant response concerning the carbon sequestration through cropping systems but is relatively more variable in response to treatments and location-specific constraints, including soil water and temperature regimes (Basheer et al., 2024).

Overall, the variance captured by the three components (83.7%) shows that the PCA captured most of the variance in the data. After varimax rotation, the loadings of each component were clear and reasonable, with each variable loading heavily on a single component, which enabled the identification of underlying dimensions. The PCA results are in line with the regression and correlation analysis results, which showed that the 3 most dominating pillars of agricultural sustainability under the context of carbon sequestering management practices are soil carbon accumulation, crop productivity, and mitigating greenhouse gas. These dimensions are all related; soil organic matter, which plays a key role in production and environment, links the three dimensions. The PCA therefore provides a simple-reduction system to explain the multivariate function of the practices tested and helps to decide which management methods to use to obtain the best results in terms of different sustainability dimensions.

### ***Comparative Findings***

The performance of the soil carbon sequestration practices was then compared to the conventional farming control system to give this performance a perspective of the whole farming enterprise. This comparative analysis assessed the extent of improvements over the sustainability indicators, giving a clear baseline that can be used to measure improvements from the carbon sequestering management strategies. The practices led to substantial and significant improvements on all the dimensions of agroecosystem performance measured, as shown in Table 2, and the improvements were statistically significant.

**Table 2.** Comparative performance of soil carbon sequestration practices versus conventional farming systems.

| Indicator                                                                                | Conventional Farming | Carbon Sequestration Practices | Percent Change |
|------------------------------------------------------------------------------------------|----------------------|--------------------------------|----------------|
| Soil Organic Carbon (g kg <sup>-1</sup> )                                                | 11.2                 | 14.9                           | +32.8%         |
| Soil Health Index (0–100)                                                                | 52.4                 | 66.7                           | +27.4%         |
| Crop Yield (Mg ha <sup>-1</sup> )                                                        | 3.8                  | 4.8                            | +26.3%         |
| Water-Use Efficiency (kg ha <sup>-1</sup> mm <sup>-1</sup> )                             | 12.5                 | 15.2                           | +21.6%         |
| Net Greenhouse Gas Emissions (kg CO <sub>2</sub> -eq ha <sup>-1</sup> yr <sup>-1</sup> ) | 4,210                | 3,334                          | -20.8%         |

Concurrently, soil organic carbon (SOC) is seen to have risen from the soils of conventional farming systems (11.2 g kg<sup>-1</sup>) to that of sequestered soils (14.9 g kg<sup>-1</sup>), representing a 32.8% rise in SOC concentration. This large soil carbon pool has arisen due to several factors all potentially related, such as reduced tillage, increased organic matter input and increased microbial activity, which are all likely to lead to an increase in the soil matrix and organic matter stability (Lal et al., 2007). The benefits of carbon sequestration, however, are not only the carbon stored in the carbon pool but also other soil fertility parameters like soil nitrogen, phosphorus, potassium and other micronutrients, physical structure and biological activity (Doran & Zeiss, 2000). This research agrees with others (e.g., Wang et al., 2010), who found that more than one soil health indicator can be beneficially affected by conservation agriculture.

The crop yield was also found to be significantly higher (26.3%) in the treated plots than in the control plots; the mean yield was 4.8 Mg ha<sup>-1</sup> in treated plots compared to 3.8 Mg ha<sup>-1</sup> in the control plots. This is important because it demonstrates such a gain in productivity would not compromise yield – a primary concern for growers when considering conservation agriculture (Wezel et al., 2025). Rather, it seems the increased organic matter improves soil health and nutrient cycling to foster soil conducive to crop growth, which contributed to higher productivity (Raihan, 2023). The other advantage of these practices is an increase in water-use efficiency from 12.5 kg ha<sup>-1</sup> mm<sup>-1</sup> to 15.2 kg ha<sup>-1</sup> mm<sup>-1</sup>, or 21.6%. This increased WUE is due to the increased water-holding capacity in the soil and a reduction in evaporative loss with increased organic matter in the soil (Hatfield & Dold, 2019).

Most importantly, when considering climate mitigation, the practices of carbon sequestration decreased the amount of GHGs from 4,210 to 3,334 kg CO<sub>2</sub>-equivalent ha<sup>-1</sup> yr<sup>-1</sup>, a 20.8% drop. This decrease was attributed to lower CO<sub>2</sub> emissions from reduced soil disturbance, lower N<sub>2</sub>O emissions from improved N management and, in some instances, higher efforts of well-aerated soils in absorbing CH<sub>4</sub> (Basheer et al., 2024). This magnitude of decreased emissions is estimated to be consistent with previous studies of the emission reduction potential of conservation agriculture vs. traditional tillage (15-30%) (Lal et al., 2007). The net climate benefit is, however, larger because of the extra benefit of carbon sequestration in soil due to such practice and the smaller climate impact from reduced GHG emissions on treated land and CO<sub>2</sub> sequestration in the atmosphere.

## Discussion

The results of this detailed field study have great implications both for the theoretical understanding of soil carbon dynamics and for the management of agricultural systems. Since soil organic carbon was the most suitable predictor for agricultural sustainability as indicated by the regression analysis, it follows that it can be used as a central element connecting various ecosystem services (Lal et al., 2007), a relation that could be considered a conceptual framework. The three major entity components, soil, C accumulation, crop productivity and GHG mitigation, indicate a simplified, overarching idea about the impact of CS methods on the agroecosystems' performance. This multi-dimensional structure also indicates that sustainability assessments should go beyond using a single indicator and implement integrated approaches that take into account the synergies of managing soil, crops and environment. The findings from this research are important for farmers, for agricultural advisors and for agriculture policies wishing to support sustainable land use. The result that SOC also emerged as the indicator most highly correlated with agricultural sustainability suggests that tracking and improving the SOC stocks should be key goals for agricultural management programmes. The Soil Carbon Sequestration Index could be used as a practical indicator for evaluating the sustainability of farming systems and as a screening tool to identify potential additional carbon sequestration strategies. The calculated 20.8% reduction of net greenhouse gas emissions (GHGs) in agriculture can be used by policymakers to inform the development of plans to include agricultural soil carbon sequestration in their climate mitigation actions plans, including nation-determined contributions (Nationally Determined Contributions, NDCs) under the Paris Agreement (Antle & Diagana, 2003). Low CV of ASI scores indicated that the practices had a consistent performance across the different agroecological zones, suggesting that the value of these practices is more widely transferable; however, site-specific adaptation of combinations of practices may be needed to optimise results.

But there are certain methodological drawbacks to consider in analysing the above. The three-year study duration is appropriate to identify initial treatment effects but may be too short to capture the processes of soil carbon sequestration that can go on for decades to reach equilibrium (Khan et al., 2021). Although experiments were designed quite comprehensively, field experiments were conducted on research farms under fairly homogeneous settings and management, meaning that inclusion of different farmers' decisions or provision of resources as found in the field, in particular, would have been insufficient. In our research, we included

18 research farms in different agroecological zones; therefore, our results could be generalised, but the type of soils and climatic conditions tested may not be applicable to other sites where these practices may be applied. Furthermore, using AWs for monitoring GHGs, as it is done in some of the studies, can result in good data for the GCs, but it may fail to capture the heterogeneity of GHGs within the plots, especially nitrous oxide, which is known to be highly spatially variable (Basheer et al., 2024). Statistical imputation (2.3%) of the missing data values may have resulted in a certain bias in estimating the treatment effect, particularly because when extreme weather (such as the heat wave or the flood) has sparse missing data values for some variables.

In this study, it has been determined that there are some areas of gaps and inconsistencies, and that can be a reason for further studies. It is important to have longer-term experimental studies (10 years or more) to monitor soil carbon build-up and the sustainability outcome beyond the project implementation stage. These studies may help determine the trend plot of a linear rate of return or a point where values would level off and whether or not there would be any productivity increase without further input. Moreover, the research should examine combinations of different carbon-sequestering practices, as those experimented with in this study are implemented separately, and is not tested systematically. The regression analysis suggested that application of organic amendment together with conservation tillage (CT) might exhibit a synergic effect; however, the combinations of these and their respective performances under various conditions have not been studied enough. To date, socio-economic aspects of adoption have been pending – such as labour requirements, economic benefits of carbon-sequestration technology vs. traditional agriculture and input price. To arrive at a broader sense of the trade-offs and synergies of the shift to sustainable agriculture systems, research incorporating biophysical measurements and farm-level economic analysis is needed. Moreover, future research is needed to better understand how soil carbon sequestration practices can reduce stress on produced crops, as quality measures were not fully considered in this study, e.g., the protein content, concentration of micronutrients and phytochemical profile of produced crops.

## Conclusion

This is a study with solid empirical evidence showing that measures taken to sequester soil carbon markedly improve the sustainability of farming in various agroecological areas. Based on our findings, we concluded that conservation-orientated management practices, especially, can decrease GHG, boost SOC, soil health, and water use efficiency, and enhance yield. The inclusion of the three main components of the ASI that account for 83.7% of the variance in the significant predictive model for soil organic carbon brings multi-dimensional tools that allow us to understand how these practices affect the performance of the agroecosystems. The observed 32.8% increase in soil organic carbon and 20.8% reduction in the net GHG emissions have shown the ability of the C-sequestering practices to meet with both the goals of food security and climate mitigation without trade-offs between productivity and environment. These results support the existing body of evidence to indicate the need for integrating soil carbon management in the agricultural policy context or national climate strategies.

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