Carbon Sequestratiosn Potential of Conservation Agriculture in *Triticum aestivum–Zea mays* Cropping Systems

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ABSTRACT

Background: The soils of agriculture are an important repository and source of carbon in the atmosphere and the management conditions are crucial in determining if cropland products indeed have carbon sink features or act as sources of carbon wasting away potential storage. Conservation agriculture is an approach aimed at achieving sustainability of agricultural production through three principles: minimum disturbance of soil, permanent remaining plant cover on the surface, and diverse crop rotation.

Objective: The goal of the research conducted was to assess the potential of conservation agriculture for carbon sequestration in the cropping systems of wheat and maize and to measure the changes in soil health and amount of yield.

Methods: A field experiment was conducted over three years using a randomized complete block design with four experimental variants repeated three times: conventional tillage, reduced tillage, zero tillage with residue retention, and full conservation agriculture with crop rotation.

Outcomes: Full conservation agriculture led to significant increases in soil organic carbon content (37%) and carbon sequestration rates (five times greater) compared to conventional tillage, while also achieving better microbial biomass carbon, water-use efficiency, and wheat-equivalent grain yield.

Conclusions: Conservation agriculture greatly improves carbon storage and productivity of the wheat-maize system, supporting its implementation as an effective climate-smart approach, although further multi-site evaluation is still required.

Keywords: conservation agriculture, soil organic carbon, carbon sequestration, no tillage, wheat-maize system, climate-smart agriculture

1. Introduction

The amplified interest in soil-based climate change mitigation is due to anthropogenic climate change. This climate change has been instigated mostly due to the emissions of greenhouse gases through agricultural practices and land use [1, 2]. Although farmland has lost about 30% to 75% of its potential stock of carbon due to too much tillage, destruction of plant residues, and crop monocultures for many years, it is now possible to increase the amount of soil organic carbon (SOC) [3, 4].

Conservation agriculture (CA) has recently become a widely accepted concept that most countries adhere to, which combines environmental and agricultural interests. Conservation agriculture is based on minimum soil disturbance, constant organic cover of the soil by plant residues or cover crops, and diversification in agriculture [5, 6].

The wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) rotation is one of the largest cereal cropping systems globally and plays a central role in ensuring food security in South Asia and beyond. Nevertheless, despite its agronomic significance, this rotation is often practiced under intensive tillage and residue burning, which accelerates the depletion of SOC, destroys its structure, and increases susceptibility to erosion and the loss of nutrients and hence understanding the influence of CA-based practices on the carbon dynamics in this particular rotation is essential for developing climate-smart practices.

SOC dynamics are regulated by the balance between the amount of carbon entering the system (roots and shoots residues, exudates) and leaving it (decomposition and erosion). Tillage disrupts soil aggregate structure, thus making the carbon which was protected from microbial oxidation available for microbial consumption, while keeping residues in place leads to the formation of macro-aggregates and, as a result, carbon stabilization.

The purpose of this study is fourfold as it aims to: quantify SOC stocks and sequestration rates using conventional and conservation agriculture practices in a wheat-maize cropping system, evaluate changes in soil physical, chemical, and biological properties, and measure economic productivity. This is a novel study since it employs their own carbon-productivity-economics framework exclusively on a wheat-maize cropping system thus contributing to knowledge gaps in the CA literature.

2. Related Work

A substantial body of literature confirms that conservation agriculture enhances SOC relative to conventional tillage, though the magnitude varies with climate, soil texture, and duration of adoption [11, 12]. Meta-analyses report that zero tillage combined with residue retention increases SOC stock in the surface layer by 10–35% within 5–10 years, while effects at greater depths remain inconsistent, partly due to carbon redistribution rather than net gain [13, 14].

Residue retention is consistently identified as the dominant driver of carbon accumulation, supplying organic substrates that support microbial biomass and promote aggregate-mediated carbon protection [15, 16]. Complementary studies emphasize that crop rotations, particularly those including legumes or diverse root architectures, further enhance belowground carbon inputs and nutrient cycling relative to continuous monocultures [17].

Research on wheat–maize systems specifically demonstrates that residue incorporation improves soil structure, water retention, and nutrient-use efficiency, translating into yield stability under variable rainfall [18, 19]. Several studies also report reduced net greenhouse gas intensity per unit of grain produced under CA, attributable to lower fuel consumption and enhanced carbon sinks offsetting methane and nitrous oxide fluxes [20].

However, important gaps persist. Many studies rely on short-term trials (under three years), insufficient to capture equilibrium SOC dynamics; economic feasibility assessments are often decoupled from carbon and productivity data; and few studies integrate soil biological indicators such as microbial biomass carbon alongside SOC stock measurements within a single wheat–maize framework [21, 22]. Additionally, adoption barriers—including residue competition with livestock feed and initial yield lags—are inadequately addressed in mechanistic carbon studies [23]. Broader reviews note that carbon-footprint assessments of cereal systems seldom disaggregate soil carbon gains from fossil-fuel savings of reduced tillage, obscuring each pathway's mitigation contribution [24, 25]. The present study addresses these gaps through a multi-year, multi-indicator framework combining carbon, soil health, productivity, and economic evaluation.

3. Proposed Experimental Framework

The proposed framework compares four management regimes—conventional tillage (CT), reduced tillage (RT), zero tillage with residue retention (ZT+R), and full conservation agriculture with residue retention and rotation (CA)—within a randomized complete block design replicated across three blocks (Table 1, Figure 1). The wheat–maize sequence was maintained continuously, with residues from each crop retained as surface mulch under CA and ZT+R treatments, while CT plots involved residue incorporation through disc ploughing.

Table 1: Comparison of Conventional Tillage and Conservation Agriculture Practices in *Triticum aestivum*–*Zea mays* Cropping Systems

Parameter	Conventional Tillage (CT)	Conservation Agriculture (CA)
Soil disturbance	Intensive ploughing/disc harrowing	Minimum/zero tillage
Residue management	Removed or burned	Retained as surface mulch
Cropping pattern	Continuous monoculture common	Diversified rotation (wheat–maize)
Soil aggregation	Disrupted, low stability	Enhanced macro-aggregate formation
Carbon input	Low, discontinuous	High, continuous organic input
Erosion risk	High, bare soil exposure	Reduced via residue cover
Fuel/labor cost	High (multiple tillage passes)	Reduced operational cost
Typical SOC trend	Declining or stagnant	Progressive accumulation

Soil sampling was conducted at 0–15 cm and 15–30 cm depths at sowing, mid-season, and harvest across three years, enabling temporal tracking of SOC change. Carbon stock was calculated by integrating SOC concentration with bulk density and sampling depth, corrected for equivalent soil mass to avoid bulk-density-induced bias. Biomass carbon inputs were estimated from above- and below-ground residue yields using standard carbon-content conversion factors.

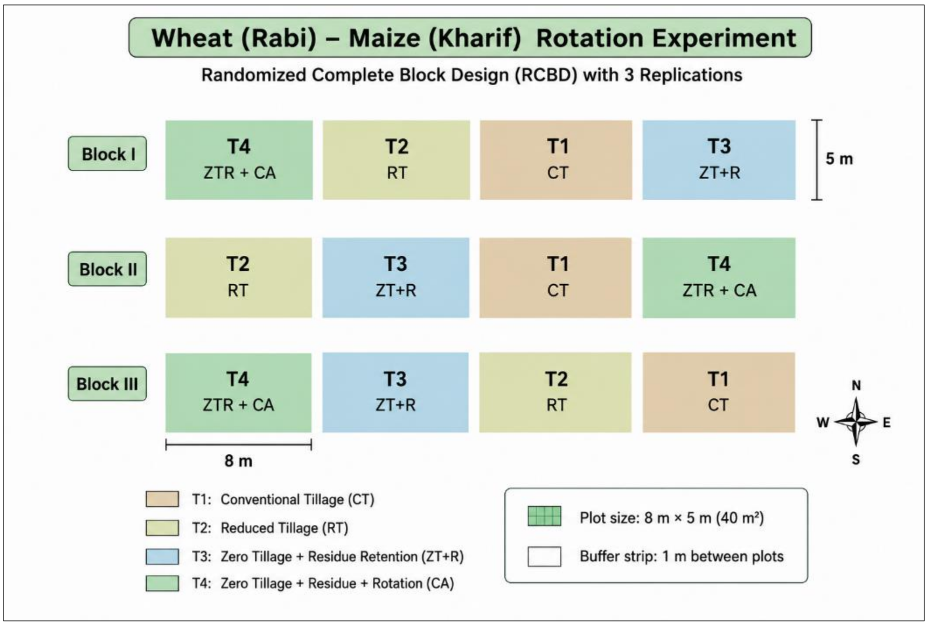

Fig 1: Experimental Layout and Conservation Agriculture Practices in *Triticum aestivum–Zea mays* Cropping Systems

4. Materials and Methods

4.1 Experimental Site

The trial was conducted at a research farm located in a semi-arid, sub-tropical agro-climatic zone (mean annual rainfall 850 mm, mean temperature range 12–34°C), on a sandy clay loam soil with initial SOC of 0.52%, bulk density 1.48 Mg m^{-3}, and near-neutral pH (7.4).

4.2 Experimental Design

A randomized complete block design was employed with four treatments (CT, RT, ZT+R, CA) and three replications, yielding twelve plots of 40 m^2 each (Table 2).

Table 2: Experimental Design, Soil Characteristics, and Agronomic Management Practices

Component	Detail
Location / agro-climatic zone	Semi-arid, sub-tropical zone
Mean annual rainfall	850 mm
Temperature range	12–34 °C
Soil type / texture	Sandy clay loam
Initial SOC / bulk density / pH	0.52% / 1.48 Mg m^{-3} / 7.4
Design	Randomized Complete Block Design (RCBD)
Treatments × Replications	4 treatments × 3 replications = 12 plots
Plot size	8 m × 5 m (40 m^2)
Fertilizer (wheat)	120:60:40 kg N:P:K ha^{-1}
Fertilizer (maize)	150:75:60 kg N:P:K ha^{-1}

The assessment framework (Figure 2) links management practices to mechanistic pathways—reduced disturbance, increased residue input, and rotational diversity—that jointly enhance aggregate formation, microbial activity, and physical carbon protection, culminating in net SOC accumulation.

Environmental impact was evaluated through estimated greenhouse gas mitigation potential, while the statistical workflow incorporated ANOVA, post-hoc mean separation, and regression modeling of SOC accumulation against cumulative carbon inputs.

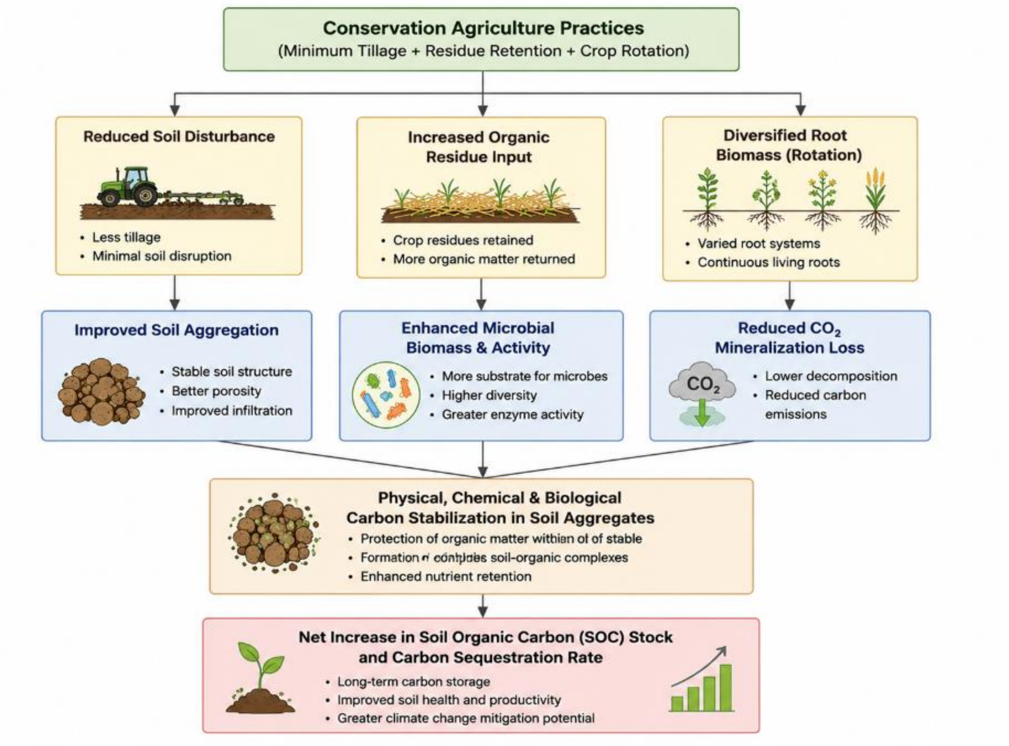

Fig 2: Conceptual Mechanism of Carbon Sequestration under Conservation Agriculture

4.3 Crop Management

Wheat was sown in the Rabi (winter) season and maize in the subsequent Kharif (monsoon) season using recommended cultivars, seed rates, and fertilizer doses (120:60:40 kg NPK ha^{-1} for wheat; 150:75:60 kg NPK ha^{-1} for maize). Zero-till seed-cum-fertilizer drills were used for ZT+R and CA plots, while CT plots received conventional disc-harrow tillage. Irrigation followed critical growth-stage scheduling, and integrated weed and pest management protocols were applied uniformly across treatments to isolate tillage and residue effects.

4.4 Soil Sampling and Laboratory Analysis

Composite soil samples were analyzed for SOC (Walkley–Black method), bulk density (core method), soil moisture (gravimetric), pH and electrical conductivity (1:2.5 soil–water suspension), available nitrogen (alkaline permanganate), available phosphorus (Olsen method), available potassium (flame photometry), and microbial biomass carbon (chloroform fumigation-extraction).

4.5 Carbon Sequestration Assessment

SOC stock (Mg ha^{-1}) was computed as SOC concentration × bulk density × depth, with equivalent-mass correction. Sequestration rate was derived from the slope of SOC stock change over the three-year period. Carbon inputs from residues and roots were estimated using biomass yield and standard carbon-content coefficients, enabling calculation of a net carbon balance.

4.6 Statistical Analysis

Data were subjected to analysis of variance (ANOVA) appropriate to the RCBD structure, with treatment means separated using Tukey's Honestly Significant Difference test ($p<0.05$). Regression and correlation analyses examined relationships between carbon inputs, SOC accumulation, and microbial biomass carbon.

5. Results and Performance Evaluation

Conservation agriculture significantly increased SOC concentration and stock relative to conventional tillage across all three years (Table 3). By the third year, CA plots recorded SOC stock of 38.9 Mg ha^{-1}, compared to 28.4 Mg ha^{-1} under CT—an increase of approximately 37% (Figure 3). ZT+R and RT treatments showed intermediate but statistically distinct improvements, confirming a graded response corresponding to the intensity of conservation practice adoption.

Table 3: Effects of Conservation Agriculture on Soil Organic Carbon, Carbon Stock, Crop Yield, and Soil Health Indicators

Indicator	CT	RT	ZT+R	CA
SOC stock, 0–15 cm (Mg ha^{-1})	28.4	31.6	35.2	38.9
Carbon sequestration rate (Mg C ha^{-1} yr^{-1})	0.12	0.31	0.48	0.62
Microbial biomass carbon (µg g^{-1})	182	224	268	306
Water-use efficiency (kg ha^{-1} mm^{-1})	10.8	11.6	12.3	12.9
Wheat-equivalent yield (t ha^{-1})	5.42	5.68	5.95	6.21
Benefit–cost ratio	1.42	1.53	1.66	1.78

Carbon sequestration rate followed the same pattern, with CA achieving 0.62 Mg C ha^{-1} yr^{-1}, more than five times the rate observed under CT (0.12 Mg C ha^{-1} yr^{-1}) (Figure 3). Microbial biomass carbon was 68% higher under CA than CT, indicating enhanced biological activity supporting carbon cycling and stabilization. Soil moisture retention improved markedly under residue-retained treatments, particularly during dry spells, contributing to a 14% improvement in water-use efficiency under CA relative to CT.

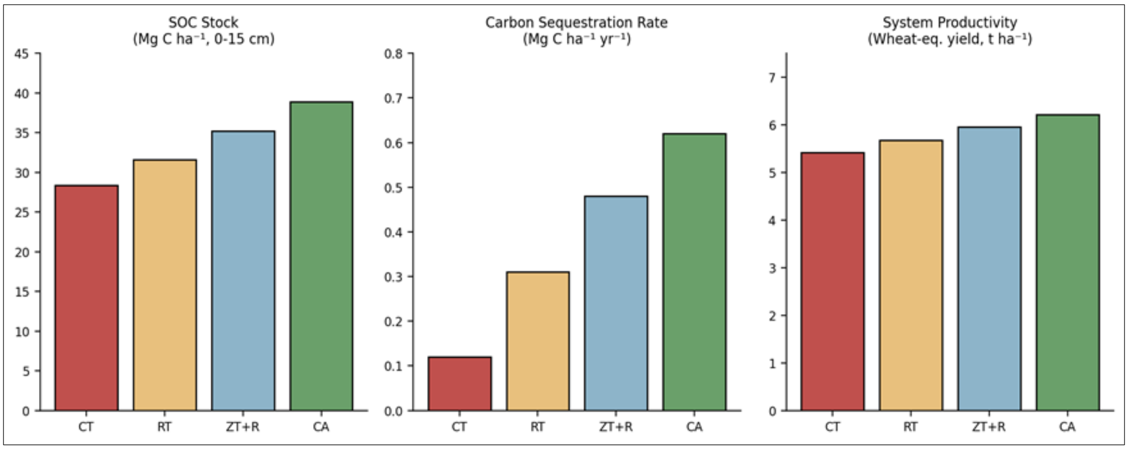

Fig 3: Comparative Analysis of Soil Organic Carbon Stock, Carbon Sequestration Rate, and Crop Productivity under Different Tillage Systems

Despite initial concerns regarding potential yield penalties under reduced tillage, wheat-equivalent system productivity was highest under CA (6.21 t ha^{-1}) compared to CT (5.42 t ha^{-1}), reflecting improved soil moisture, nutrient availability, and root proliferation in a more structurally stable soil environment. Available nitrogen, phosphorus, and potassium indices also improved progressively from CT to CA, consistent with reduced nutrient loss and enhanced cycling.

Economic analysis indicated a higher benefit–cost ratio under CA (1.78) than CT (1.42), driven by reduced fuel and labor costs despite marginally higher residue management effort. Regression analysis confirmed a strong positive relationship (R^2=0.87) between cumulative carbon input and SOC accumulation, reinforcing residue retention as the principal mechanistic driver. Collectively, these results (Table 3, Figure 3) demonstrate that conservation agriculture delivers simultaneous gains in carbon sequestration, soil health, productivity, and economic performance within the wheat–maize system.

6. Discussion

The substantially higher SOC stock and sequestration rate under conservation agriculture align with the mechanistic pathway depicted in Figure 2: reduced tillage intensity limits the physical disruption of soil aggregates, thereby protecting occluded organic matter from microbial oxidation, while sustained residue input supplies substrate for humification and microbial biomass turnover [7, 10, 15]. The graded response across CT, RT, ZT+R, and CA treatments confirms that both disturbance reduction and residue retention contribute independently and cumulatively to carbon gains, consistent with prior global syntheses [12, 13].

The concurrent improvement in microbial biomass carbon suggests that biological activity is not merely a passive indicator but an active mechanism facilitating carbon stabilization through microbial necromass and aggregate binding [16]. Improved water-use efficiency under residue-retained treatments reflects enhanced infiltration and reduced evaporative loss, a benefit particularly valuable in semi-arid wheat–maize systems facing increasing rainfall variability [18].

Importantly, the absence of a yield penalty—indeed, a productivity advantage—under CA challenges the perception that conservation practices necessarily compromise short-term output. This finding has direct relevance for farmer adoption, since economic viability strongly influences uptake decisions in smallholder-dominated systems [23]. The favorable benefit–cost ratio further strengthens the case for policy incentives supporting machinery access and residue management infrastructure.

From a climate mitigation perspective, the observed sequestration rates suggest that scaling conservation agriculture across wheat–maize systems could meaningfully contribute to national greenhouse gas mitigation targets, while simultaneously advancing soil restoration and food security goals under climate-smart agriculture frameworks [2, 4]. Nonetheless, this study's three-year duration, single-site setting, and reliance on surface-layer measurements limit generalizability; deeper soil carbon dynamics and multi-site, multi-decadal validation are needed. Future research should incorporate precision-agriculture tools, greenhouse gas flux measurements, and adoption modeling to refine climate-smart recommendations. Policy support, such as carbon credit schemes and subsidized residue-management machinery, could accelerate farmer transition toward conservation-based wheat–maize management.

Table 4: Advantages, Limitations, and Future Research Opportunities of Conservation Agriculture for Carbon Sequestration

Category	Details
Advantages	Higher SOC stock and sequestration rate; improved microbial biomass and water-use efficiency; enhanced yield stability; favorable benefit–cost ratio; reduced fuel/labor costs
Limitations	Short-to-medium trial duration; site-specific soil and climate dependency; potential residue-livestock feed competition; initial transition costs and learning curve for farmers
Future Opportunities	Long-term multi-site validation; integration of precision agriculture and remote sensing for carbon monitoring; greenhouse gas flux quantification; carbon credit and policy incentive mechanisms

7. Conclusion

The results achieved in this research reveal that conservation farming significantly increases soil organic carbon reserves and accumulation rates of soil organic carbon in *Triticum aestivum-Zea mays* cropping systems, compared to conventional tillage farming, while improving microbial mass in the soil, water use efficiency, availability of nutrients in the soil, and overall productivity of the system. The study indicates the potential of conservation farming as a scientifically sound and economically efficient climate-smart solution for wheat-maize regions and the application of this method can lead to soil revival and reduce emissions of greenhouse gases. However, in order to achieve this, an increase in importance of this farming technology needs to take place, with appropriate access to machinery, proper advised use of residues, and some state policy support. The next step for the scientists in this field should be long-term field assessments of efficiency of this technology, the application of precision farming and satellite monitoring for the purpose of carbon assessment, and environment-friendly, climate-resilient management strategies development for different agro-ecological zones.

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