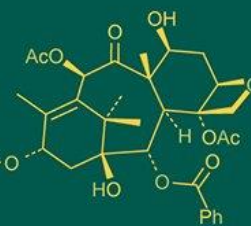
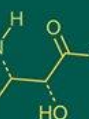
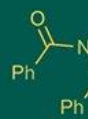


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Impact of conservation tillage and crop diversification on soil organic carbon and CEC under maize-based systems in a *Typic Haplustept*

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Abstract

A long-term field study (2018-2019) was conducted to assess the impact of conservation agriculture (CA) practices on soil organic carbon (SOC) and cation exchange capacity (CEC) in a *Typic Haplustept* under maize-based cropping systems. The experiment followed a split-plot design with three replications, including three tillage and crop establishment (TCE) methods—zero till permanent bed (PB), zero till flat (ZT), and conventional tillage flat (CT)—and four diversified cropping systems. Soil samples collected from three depths (0-5, 5-15, and 15-30 cm) revealed significant improvements in SOC and CEC under conservation tillage with residue retention. Zero tillage (PB and ZT) combined with maize-chickpea-sesbania (MCS) and maize-wheat-mungbean (MWMB) systems substantially enhanced SOC and CEC relative to conventional tillage. Results suggest that CA practices positively influence soil fertility and sustainability in semi-arid maize-based systems.

Keywords: Conservation agriculture, zero tillage, soil organic carbon, Cation exchange capacity, cropping system, *Typic Haplustept*

Introduction

Soil fertility decline and degradation of soil health are major challenges in intensive maize-based cropping systems under semi-arid subtropical conditions. Continuous conventional tillage, residue removal, and cereal-dominated rotations accelerate organic matter decomposition and nutrient depletion, thereby reducing soil productivity and sustainability (Lal, 2015) [8]. Conservation agriculture (CA), based on minimum soil disturbance, residue retention, and crop diversification, has emerged as a sustainable strategy for improving soil health and resource-use efficiency in the Indo-Gangetic Plains.

Soil organic carbon (SOC) is an important indicator of soil quality as it influences nutrient cycling, aggregation, microbial activity, and water-holding capacity. Long-term adoption of reduced tillage with residue retention enhances SOC accumulation by minimizing oxidation losses and increasing carbon inputs through crop residues (Jat *et al.*, 2013) [6]. In coarse-textured *Typic Haplusteps*, maintenance of SOC is particularly important for sustaining soil fertility. Cation exchange capacity (CEC) reflects the soil's ability to retain and exchange nutrient cations and is strongly influenced by soil organic matter content. Increased SOC under conservation agriculture may therefore improve nutrient retention and fertilizer-use efficiency (Pooniya *et al.*, 2021) [9]. Inclusion of legumes such as chickpea, mungbean, and sesbania in crop rotations further enhances soil quality through biological nitrogen fixation and improved residue quality (Akshith *et al.*, 2024) [11]. Therefore, the present study was conducted to evaluate the long-term effects of conservation tillage and diversified maize-based cropping systems on SOC and CEC in a *Typic Haplustept*.

Materials and Methods

Site Description

The present investigation was conducted under a long-term conservation agriculture experiment initiated during 2008 at the research farm of the Indian Institute of Maize

Research, New Delhi, India. The study site falls under a semi-arid subtropical climatic zone and receives about 1065 mm annual rainfall, predominantly during the monsoon months (July to September). The experimental soil was classified as *Typic Haplustept* (Inceptisol) with sandy loam texture. At the beginning of the experiment, the soil contained 64.3% sand, 13.8% silt, and 22.0% clay, with an initial pH of 7.8, bulk density of 1.65 Mg m^{-3} , and soil organic carbon content of 4.31 g kg^{-1} . The experiment was established to study the long-term influence of tillage and maize-based cropping systems on soil properties under conservation agriculture practices.

Experimental Design

The study followed a split-plot design with three replications:

Main plots (TCE methods)

- Zero till permanent bed with residue (PB)
- Zero till flat with residue (ZT-flat)
- Conventional till flat with residue (CT-flat)

Subplots (Cropping systems)

- Maize-wheat-mungbean (MWMb)
- Maize-chickpea-sesbania (MCS)
- Maize-mustard-mungbean (MMuMb)
- Maize-maize-sesbania (MMS)

Sampling and Analysis

Soil samples were collected from three depths (0-5 cm, 5-15 cm, and 15-30 cm) after completion of the cropping cycle. The collected samples were air-dried, ground, and passed through a 2-mm sieve before laboratory analysis. Soil organic carbon (SOC) was determined using the Walkley and Black (1934) ^[11] dichromate oxidation method, while cation exchange capacity (CEC) was measured by the 1 N ammonium acetate extraction method following Jackson (1973) ^[5]. The experimental data were subjected to analysis of variance (ANOVA) appropriate for a split-plot design, and treatment means were compared using the Least Significant Difference (LSD) test at the 0.05 probability level.

Results

Effect on Soil Organic Carbon (SOC)

SOC content varied significantly across tillage and cropping systems (Table 1). Among TCE methods, PB (6.27, 5.51, 4.85 g kg^{-1}) and ZT-flat (6.13, 5.28, 4.92 g kg^{-1}) recorded markedly higher SOC values than CT-flat ($4.96, 4.70, 4.28 \text{ g kg}^{-1}$) across depths. Across cropping systems, MCS and MWMb exhibited higher SOC accumulation, while MMuMb and MMS recorded significantly lower SOC levels. Enhanced residue retention and legume integration likely contributed to carbon buildup in MCS and MWMb systems.

Effect on Cation Exchange Capacity (CEC)

CEC followed a similar trend to SOC (Table 2). Conservation tillage treatments PB ($15.7 \text{ cmol kg}^{-1}$) and ZT-flat ($15.4 \text{ cmol kg}^{-1}$) maintained higher exchange capacity than CT-flat ($13.2 \text{ cmol kg}^{-1}$) at surface depth. Diversified systems MCS ($16.1 \text{ cmol kg}^{-1}$) and MWMb ($15.3 \text{ cmol kg}^{-1}$) outperformed others, signifying the role of legume inclusion and organic inputs in enhancing cation exchange sites (Wei

et al., 2014) ^[12]. The strong correlation between organic carbon and CEC underscores the integral role of organic matter in nutrient retention (Ghosh *et al.*, 2010) ^[3].

Discussion

The significant increase in SOC and CEC under conservation agriculture practices highlights the beneficial effects of reduced tillage, residue retention, and crop diversification on soil quality improvement. Permanent beds and zero-tillage systems maintained higher SOC levels compared to conventional tillage because minimal soil disturbance reduced oxidation and decomposition of organic matter (Lal, 2015) ^[8]. Surface retention of crop residues under conservation agriculture continuously supplied carbon substrates to the soil and promoted microbial activity, thereby enhancing carbon sequestration and soil fertility. The higher SOC accumulation in surface layers under PB and ZT systems is consistent with findings reported by M. L. Jat *et al.* (2011) ^[7], observed greater carbon build-up under long-term conservation agriculture in the Indo-Gangetic Plains. Reduced tillage also improves soil aggregation, which physically protects organic carbon from microbial decomposition and increases stabilization of soil organic matter (Sapkota *et al.*, 2012) ^[10].

Cropping system diversification significantly influenced SOC and CEC, particularly under legume-inclusive systems such as maize-chickpea-sesbania and maize-wheat-mungbean. Legumes contribute to biological nitrogen fixation and produce residues with relatively low C:N ratio, which decompose rapidly and improve soil organic matter dynamics. Similar observations were reported by Wei *et al.* (2014) ^[12] and Araya *et al.* (2021) ^[2].

The improvement in CEC under conservation tillage and diversified cropping systems may be primarily associated with increased SOC content. Organic matter contributes a substantial proportion of the soil's negative charge density and therefore increases nutrient retention capacity. Higher SOC under PB and ZT systems consequently resulted in greater CEC values. Similar relationships between SOC and CEC were reported by Ghosh *et al.* (2013) ^[3].

In contrast, conventional tillage resulted in lower SOC and CEC values due to intensive soil disturbance, breakdown of aggregates, and accelerated mineralization of organic matter. Frequent tillage exposes protected organic carbon to microbial decomposition, reducing long-term carbon storage and nutrient retention capacity. These findings demonstrate that long-term conservation agriculture practices can substantially improve soil fertility and sustainability in *Typic Haplustepts* under maize-based cropping systems.

Table 1: Long-term effect of tillage and cropping systems on soil organic carbon (g kg^{-1})

Treatments	0–5 cm	5–15 cm	15–30 cm
Tillage			
PB	6.27 ^a	5.51 ^a	4.85 ^a
ZT-flat	6.13 ^a	5.28 ^a	4.92 ^a
CT-flat	4.96 ^b	4.70 ^b	4.28 ^b
LSD (0.05)	0.66	0.52	0.48
Cropping system			
MWMb	6.82 ^a	6.17 ^a	5.67 ^a
MCS	7.11 ^a	6.39 ^a	5.88 ^a
MMuMb	4.74 ^b	4.14 ^b	3.49 ^b
MMS	4.47 ^b	3.94 ^b	3.68 ^b
LSD (0.05)	0.48	0.37	0.32

Table 2: Long-term effect of tillage and cropping systems on cation exchange capacity (cmol kg⁻¹)

Treatments	0–5 cm	5–15 cm	15–30 cm
Tillage			
PB	15.7 ^a	13.0 ^a	11.0 ^a
ZT-flat	15.4 ^a	12.7 ^a	11.2 ^a
CT-flat	13.2 ^b	10.7 ^b	9.53 ^b
LSD (0.05)	1.87	1.47	1.34
Cropping system			
MWMB	15.3 ^a	12.8 ^a	11.0 ^a
MCS	16.1 ^a	13.4 ^a	11.3 ^a
MMuMB	14.1 ^b	11.4 ^b	9.93 ^b
MMS	13.6 ^b	11.1 ^b	10.2 ^b
LSD (0.05)	1.12	0.91	0.79

Conclusion

Over eleven years, conservation agriculture practices—particularly zero till permanent beds and zero till flats with residue—substantially enhanced SOC and CEC compared to conventional tillage. Diversified rotations involving maize-chickpea-sesbania and maize-wheat-mungbean systems proved most effective. The results demonstrate that long-term adoption of CA can maintain soil fertility and improve nutrient retention in *Typic Haplustepts*, promoting sustainability in maize-based cropping systems.

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