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SOIL ORGANIC CARBON DYNAMICS UNDER CONSERVATION AGRICULTURE BASED MAIZE-MUSTARD SYSTEM IN AN INCEPTISOL

अ. जय किशोर कुमार रेड्डी

A. JAYA KISHORE KUMAR REDDY



DIVISION OF SOIL SCIENCE AND AGRICULTURAL CHEMISTRY
ICAR - INDIAN AGRICULTURAL RESEARCH INSTITUTE

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**SOIL ORGANIC CARBON DYNAMICS UNDER CONSERVATION
AGRICULTURE BASED MAIZE-MUSTARD SYSTEM IN AN
INCEPTISOL**

BY

A. JAYA KISHORE KUMAR REDDY
Roll No. 21539

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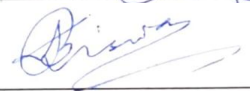
Chairman: Dr. Shrila Das



Co- Chairman: Dr. Ranjan Bhattacharyya



Members: Dr. Dipak Ranjan Biswas



Dr. Abir Dey



Dr. Tapas Kumar Das



Dr. Radha Prasanna





Division of Soil Science & Agricultural Chemistry

ICAR–Indian Agricultural Research Institute

New Delhi-110 012, India

e-mail: shrila34040@gmail.com

Dr. Shrila Das
Scientist

CERTIFICATE

This is to certify that the thesis entitled “**Soil organic carbon dynamics under conservation agriculture based maize-mustard system in an Inceptisol**” submitted to the faculty of the Post-Graduate School, Indian Agricultural Research Institute, New Delhi, in partial fulfillment of the requirements for the degree of **Master of Science in Soil Science and Agricultural Chemistry** by **Mr. A. Jaya Kishore Kumar Reddy, Roll No. 21539** embodies the results of the *bonafide* research work carried out by him under my guidance and supervision. No part of the study reported here has so far been submitted for any other degree or diploma.

It is further certified that the assistance and help received during the course of the investigation has duly been acknowledged by him.

Place: New Delhi

Date: 12/10/2022

(Dr. Shrila Das)

Chairman

Advisory Committee



*Dedicated to my family,
Chairperson
&
Advisory committee*

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1. INTRODUCTION

Agriculture around the world is witnessing several problems that are endangering sustainable food security. In past few decades, the practice of intensive cultivation using heavy implements and machinery, poor soil management and non-judicious use of chemical fertilizers were thought to be crucial to accomplish food security. Global issues such as extensive soil erosion, nutrient mining, dwindling water tables and degrading biodiversity are endangering farmers' food security and subsistence, particularly for the small and marginal farmers. One of the most serious environmental risks produced by conventional agriculture is soil degradation owing to erosion and compaction processes. This led to the concept of resource conservation, which has got worldwide acceptance to tackle this challenge while minimizing adverse impact on environment.

Conservation agriculture (CA) is a soil management practice that reduces soil erosion and degradation which helps in preservation of natural resources while optimising agriculture productivity (FAO, 2008). It enhances biodiversity and natural biological processes above and below the ground surface, which contribute to increased water and nutrient use efficiency and to improve and sustain crop production. There are three basic principles of conservation agriculture: i) minimum soil tillage, ii) permanent soil cover with crop residues and iii) crop rotation and crop diversification. Despite the fact that the Indo-Gangetic Plains (IGP) of India have a huge potential for conservation agriculture, only 2.50 M ha of it is currently under conservation agricultural practices (Jat *et al.*, 2020). In compliance with sustainability goals, CA is designed to sustain crop production in the long term while improving crop resilience to climate change and protecting the environment. Benefits of CA have been demonstrated in terms of enhancing soil carbon sequestration, improving soil quality, reducing soil erosion and increasing biodiversity (Floch *et al.*, 2007; Giller *et al.*, 2015; Das *et al.*, 2021). Conservation agriculture is responsible for the build-up of soil organic carbon (SOC) which depends on the type of and quantity of crop residues reverted to soil. The SOC dynamics has gained scientific attention, because alteration in land cover, land use and management practices can have a significant impact on global carbon pools and fluxes (Sharma *et al.*, 2014; Wijesekara *et al.*, 2017).

The SOC, being a part of natural carbon cycle, is the heart of soil health, where majority of the soil physical, chemical and biological parameters are closely intertwined to it. Therefore, maintaining and enhancing SOC is the key to sustainable agriculture. However,

most Indian soils have extremely low SOC levels, ranging from 0.3 - 0.4 %, resulting in poor soil health and low crop yields (Tigga *et al.*, 2020). Decomposition of dead plants, animals and microbes (excluding fresh plants, litter and straw) produces the organic matter in soil. Remains of plants, animals and microbes slowly decay in the soil to produce SOC. During these mineralization processes, some of the organic carbon resistant to decomposition is retained in the soil and some of the organic matter releases CO₂ back to the atmosphere (Chan *et al.*, 2008). Soil organic carbon resistant to decomposition acts as a significant stock of carbon (including about 80% of terrestrial residues of C) that plays an important role in regulation of life on planet Earth (Ontl and Schulte, 2012).

Soil organic matter (SOM) helps to increase the diversity of living organisms by providing a substrate and energy, which play an important role in maintaining soil quality and functionality in specific ecosystems such as the soil biota (Walmsley and Cerda, 2017). The fractions of SOC may be classified as: labile, semi-labile and recalcitrant exhibiting different rates of biochemical and microbial degradation (Stevenson, 1994). However, changes induced by soil management practices are often difficult to detect by total organic carbon (TOC) measurement. Assessment of rapidly changing SOC pools, *i.e.*, labile pool, might be more helpful in assessing the soil quality (Awale *et al.*, 2017; Nath *et al.*, 2017). Different portions of SOC differ from each other in carbon turnover rates, biological stability and biochemical composition (Paustian *et al.*, 1992). Labile proportions of SOM (non-humic substances) have been used as a sensitivity indicator of changes in the soil quality (Haynes, 2005). Due to significant interactions in soil systems, labile organic compounds have fast turnover rates as they serve as readily available substrates for soil microorganisms (Schmidt *et al.*, 2011), whereas more recalcitrant SOC pools are important in mitigating the ill effects of higher CO₂ concentrations in the atmosphere (Dey *et al.*, 2018).

Furthermore, SOC is also vital in the formation and stabilization of soil aggregates (Spohn and Giani, 2011). Soil aggregation and SOC accumulation are inextricably linked; SOC promotes soil aggregation, and aggregates, in turn, store SOC and slow its breakdown. Stable soil aggregates serve as the nuclei for long-term SOC stabilization, preserving the SOC by providing physical barriers between bacteria and enzymes, as a result of which the rate of SOC turn-over is slowed (Pulleman and Marinissen, 2004). The amount of carbon retained in soil is determined by the type of aggregation (Carter, 1995), degree of physico-chemical properties and organic carbon stability inside aggregates (Saha *et al.*, 2011).

As an outcome, soil aggregation is taken into account as an essential carbon sequestration process and as such, could be part of a sound solution to offset the impact of growing CO₂ concentrations in the atmosphere (Shrestha *et al.*, 2007). Hence, soil aggregate fractionation has been frequently utilized to assess SOC stability and evaluate the impacts of various soil management strategies on SOC dynamics (Kou *et al.*, 2012).

Organic carbon level of soils reaches a fixed equilibrium that is determined by a number of interacting factors such as precipitation, temperature, soil type, tillage, cropping systems, fertilizers, the type and quantity of crop residues returned to the soil, and the method of residues management. Several markers of SOC pools and enzyme activity have been utilised to evaluate SOC dynamics under tillage and crop rotation systems (Kobierski *et al.*, 2020). The SOC pool has a wide range of turnover periods and is either stabilised or shielded against microbial degradation. Pools that are active or labile have the fastest turnover times and are more responsive to land use changes than pools that are more stable (Sahoo *et al.*, 2019). Bacterial and fungal enzymes are crucial in breaking down organic stuff and transforming it into forms that can be assimilated. It is possible to determine the level of microbial activity and the contribution of microbes to nutrient cycling by the assessment of extracellular enzyme activity (EEA) (Kotroczo *et al.*, 2014). Dehydrogenase activity is considered as an indicator of oxidative metabolism in soils and, consequently, of microbiological activity (García and Hernández, 1997). Cellulose breakdown requires β -glucosidase, which is a key enzyme in plant polysaccharide metabolism. A precursor of future microbial enzyme activity, it is active during the earliest stages in degradation of organic molecules that reduces the molecular size of organic structures (Sardans *et al.*, 2008). Phenol oxidases (PO) are involved in the breakdown of several resistant aromatic compounds, and are sensitive to certain contaminants. Thus, their activity may be a good indication for assessing soil health. β -glucosidase and dehydrogenase are related with labile pools of carbon in soil, while phenol oxidase is connected with recalcitrant pools of carbon in soil (Yu *et al.*, 2012; Veum *et al.*, 2014).

With regard to the Indo-Gangetic Plains (IGP), the stability of SOC against changing temperature regimes is crucial to SOC increase under intensive farming systems. SOC decay rates at increased temperatures may be used to quantify SOC sensitivity under various soil and crop management scenarios. Soil C mineralization may be influenced by tillage, residue, and nutrient management in combination or alone .

Under diverse conditions of tillage, straw and fertilizer management, soils' response to C mineralization is necessary to manage C cycle in the soils (Cai *et al.*, 2016). Understanding the temperature sensitivity of SOC decomposition will allow us to recognise the activities that encourage soil C dynamics toward SOC build-up in the soil.

Maize-based (maize-mustard) cropping system under CA is advocated as alternate to rice-based systems in South Asia due to better suitability for diverse ecologies, higher yields with less water use and more palatable maize fodder compared to rice, and increased demand of maize from piggery and poultry industries (Parihar *et al.*, 2016). Research on the short- and medium-term effects of CA on SOC pools, carbon cycling enzymes, and soil aggregation in bulk soil in the Indo-Gangetic Plain is available. However, research on the long-term (11-years) impacts of CA on carbon pools and carbon cycling enzymes within soil aggregates and density fractions of SOM is lacking. We hypothesised that converting the traditional maize-mustard cropping system to diversified conservation agriculture improves soil organic carbon pools and carbon cycling enzymes within aggregates, stabilises added C into its pools, and increases maize-mustard productivity and profitability in IGP. Therefore, considering the above-mentioned points, we carried out a study entitled "Soil organic carbon dynamics under conservation agriculture based maize-mustard system in an Inceptisol" with the following objectives:

Objectives:

- To assess the impact of conservation agriculture on organic carbon pools and carbon cycling enzymes within soil aggregates under maize-mustard system
- To study organic carbon stabilization within soil aggregates under maize-mustard system
- To evaluate temperature sensitivity of carbon mineralization as affected by conservation agriculture practices

2. REVIEW OF LITERATURE

Maize-mustard is a productive and sustainable farming system in the Indian subtropics. Due to faulty soil management and other factors, agricultural yields are gradually declining (FAO, 2015). Our key challenge is to improve soil health to sustain food security and crop output. Soil organic carbon (SOC) is key to the soil health. This review examines conservation agriculture (CA), its effects on soil organic C pools and fractions, C cycling enzymes, aggregate distribution and aggregate associated carbon, carbon stability within aggregates, and temperature sensitivity of SOC mineralization.

2.1 Conservation agriculture

Conservation agriculture (CA) conserves and optimises natural resources. It is also a form resource-saving agricultural system, which can accomplish sustainable production with higher profit and no environmental harm. Globally ~ 125 million hectares (Mha) of land are under CA, with maximum area present in USA (26.5 Mha) followed by Brazil (25.5 Mha), Argentina (25.5 Mha), Canada (13.5 Mha), and Australia (17.0 Mha). It is estimated that a partial CA-based system (at least one crop has no till, with or without residue retention) is spread to over 2.5 million ha in South Asia (Jat *et al.*, 2020). In India's most of CA lands are in the Indo-Gangetic Plains (IGP), where wheat is zero-tilled. Adopting CA increases soil biodiversity, improves aggregation, enhances soil structure, increases SOC, and enhances pesticide biodegradation, among other benefits. Effect of CA on betterment of soil biological health has received greater attention in recent years (Jayaraman and Dalal, 2021). The CA advocates maize-based (maize-mustard) cropping systems as an alternative to rice-based systems in South Asia due to better suitability for diverse ecologies, and higher yields with less water use. Increased demand of maize from cattle, poultry and piggy industries justifies conversion of rice-based systems to maize-based systems (Parihar *et al.*, 2016).

2.2 Impacts of long-term conservation agricultural practices on soil organic carbon dynamics

Accumulation of SOC plays an important role in maintenance and improvement of agricultural productivity, and also in reduction of atmospheric carbon concentrations (Ghimire *et al.*, 2012). The labile pools of SOC *viz.*, microbial biomass carbon (MBC), dissolved organic carbon (DOC), and easily oxidizable carbon (EOC) responds to soil management intercession more rapidly than total organic carbon (TOC) (Haynes, 2005).

Hence, the labile organic fractions are considered as early sensitive indicators of quality and health of the soil (Rudrappa *et al.*, 2006; Yang *et al.*, 2005). Tillage is the mechanical manipulation of soil which is primarily done to loosen the soil for crops to grow. Following intensive tillage every season leads to long term soil disturbances which are believed to be an important factor in reducing SOC in agriculture (Baker *et al.*, 2007). Soil aggregation (macro- and micro-) and stability can have a large effect on SOC dynamics, sequestration, C availability and its storage by occluding organic residues, making them less accessible to degrading organisms and their enzymes (Six *et al.*, 2000). The CA based practices like permanent beds (PB) along with crop residue (CR) retention recorded highest share of recalcitrant carbon owing to less soil disturbance and protection of C through more stable aggregates which indicates the potential of CA based practices to stabilize SOC (Bhattacharya *et al.*, 2012; Dey, 2017).

Higher percentage of water stable macro-aggregates, macroaggregates: microaggregates ratio and aggregate carbon content are observed under zero till (ZT) crop establishment methods over conventional tillage (Naresh *et al.*, 2020). Retention of crop residue registered up to 18, 24, 5, 10 and 12% higher amounts of very labile, labile, less labile, non-labile and total SOC over non- crop residue retained plots (Nandan *et al.*, 2019). Similarly in the 0–5 cm and 5–15 cm, added residues had 25% and ~20% higher ($p < 0.05$) labile C and recalcitrant C than residue removal, respectively (Dutta *et al.*, 2022).

Soil organic C is a heterogeneous mixture of organic materials comprising labile and stabilized (i.e., recalcitrant) organic C pools based on variable turnover times (Singh and Benbi, 2018). The C dynamics is described by partitioning the soil organic matter (SOM) into physical, chemical and biological pools (Banger *et al.*, 2010). Purakayastha *et al.* (2008) found that intensive tillage oxidised labile SOM, lowering C content. Active C decomposes quickly and has a short residence time in soil, while passive C is resistant to microbial activity and changes slowly (Haynes, 2005).

The C accumulation in soils depends on many biotic and abiotic factors, such as microbial population, amount and quality of biomass added, location climate, soil management practises followed, time, *etc.* Sapkota *et al.* (2017) found that CA affected SOC stocks only in 0-5 and 5-15 cm soil layer, and not beyond. At 0-5 cm, ZT direct-seeded rice followed by ZT wheat with residue (ZTDSR-ZTW+R) and direct dry-seeded rice followed by direct drilling of wheat both on permanent beds with residue retention (PBDSR-PBW+R) had 2.4 t/ha more

SOC than conventional till transplanted rice followed by conventional till wheat (CTR-CTW). Despite many studies on the impacts of CA on SOC accumulation in the world, very limited literature is available under sub-tropical scenario with maize-based cropping system.

2.3 Impacts of long-term conservation agricultural practices on soil microbial biomass carbon

Microbial biomass C (MBC) is a key carbon fraction in multi-pool SOC dynamics models (Hanson *et al.*, 2000). Though subject to abiotic stresses (Mtambanengwe and Mapfumo, 2008), C in the soil microbial biomass pool has been used as a lability indicator and sensitive biomarker of SOC's biological activity (Banerjee *et al.*, 2006; Mazzarino *et al.*, 1991). The soil microbial biomass controls C, N, and P immobilisation and mineralization in terrestrial environments. Furthermore, MBC is a dynamic C pool in soil (1–3% of TOC) that is often the most sensitive indicator of soil quality in response to agricultural management (Souza *et al.*, 2014).

Wright and Hons (2005) reported higher values of MBC under ZT, compared with CT, with maximum effect noticed in top soil (Parihar *et al.*, 2019; Salinas-Garcia *et al.*, 2002). A 7-year trial of maize-wheat under ZT increased MBC by 13% over CT (Singh *et al.*, 2009). Similar increments in MBC were reported in rice-based systems under ZT over CT (Jiang *et al.*, 2011; Li *et al.*, 2015). Likewise, CR retention greatly enhanced MBC in soil, while crop residue removal decreased it (Chakrabarti *et al.*, 2000; Guo *et al.*, 2016; Marinari *et al.*, 2000). Aeration, temperature stability, reduced moisture variations, and increased carbonaceous substrate content in top soil were the key factors in increasing microbial population and MBC under CA (Govaerts *et al.*, 2007; Zhang *et al.*, 2018).

2.4 Impacts of long-term conservation agricultural practices on carbon cycling enzymes

Carbon cycling in soils involves biochemical, chemical and physiochemical interactions with microbes, plant roots, and soil animals mediating biochemical processes. Soil enzymes play an important role in catalyzing processes related to SOM decomposition and C cycling (Jin *et al.*, 2009). Studies on C-cycling enzymes *i.e.*, dehydrogenase (DHA), β -glucosidase, phenol oxidase *etc.* indicated that the CR and tillage management practices controls the microbial community response, mediating decomposition and the incorporation of organic carbon (OC) in stable aggregates (Almagro *et al.*, 2021). The effects of CA on enzymatic activities were mostly observed in the top 0-5 cm soil layer, whereas, at lower depths negligible effects were registered (Alvear *et al.*, 2005; Gajda *et al.*, 2013; Roldán *et al.*, 2007; Roy *et al.*, 2021). This

stratification of enzyme activities near the soil surface could be attributed to the vertical distribution of SOM, and hence the activity of microorganisms (Green *et al.*, 2007).

Dehydrogenase, an oxido-reductase enzyme found only in viable microbial cells, has been proposed as a potential indicator of soil quality due to its crucial function in soil biology, ease of measurement, and detectable response to changes in soil management practices and environmental conditions (Dick *et al.*, 1996). The ZT positively affected DHA which can be attributed to addition of crop residue (CR), and subsequent enhancement of SOM (Choudhary *et al.*, 2018; Pooniya *et al.*, 2021). Macro-aggregates (> 0.25 mm) often reported higher DHA activity than the micro-aggregates (Kussainova *et al.*, 2013; Sharma *et al.*, 2019).

The CA practices have a direct influence on the pore geometry and microbial diversity of the macro-aggregates in the rhizosphere, which directly influences the associated enzymatic activities (Crawford *et al.*, 2012; De Gryze *et al.*, 2006). Land use change from the undisturbed to cropping decreased the β -glucosidase and phenol oxidase activities in the macroaggregates (Bhattacharya *et al.*, 2021). Conceptually, the exclusion of enzymes from small pores (<1 μ m) is one of the key protection mechanisms for SOC stabilization in aggregates (Sollins *et al.*, 1996). Exclusion of enzymes reduces the SOC mineralization in the aggregates. The abundance of microbial community and enzyme activity were significantly higher in small macroaggregates, which plays a key role in the stabilisation of organic matter (OM) (Ortiz *et al.*, 2022). The β -glucosidase activity in soils is closely related to the quantity and quality of SOM, which may explain the progressively lower enzymatic activities observed under CT. The high amounts of lignified litter biomass having comparatively high C:N ratios (Hiltbrunner *et al.*, 2013) in CR retention plots are responsible for high phenol oxidase and lower β -glucosidase activity in soils. Several results indicated that soil labile-C pools and carbon cycling enzymes (β -glucosidase, dehydrogenase and phenol oxidase) across aggregate fractions were the most sensitive indicators of soil quality when determining the effects of changes in management practices.

2.5 Impacts of long-term conservation agricultural practices on soil aggregates and aggregate associated carbon

Soil aggregates are composed of primary mineral particles and organic binding agents (Haynes and Swift, 1990). At the atomic or molecular level, charged colloid surface, organic molecule, cations and water molecules bridge each other and flocculate. At the microscopic level, clay and organic matter act as bridges between the sand and silt particles, producing

microaggregates of soil (McLaren and Cameron, 1996). At macroscopic level, these microaggregates are bound together into macroaggregates by fungal hyphae, plant roots and other stabilizing agents (Oades, 1984). Soil organic carbon plays an important role in forming and stabilizing the soil structure, enhancing soil physical properties, and nutrient cycling (Naresh *et al.*, 2020).

Retention of CR on the soil surface enhances soil aggregation in comparison to the residue removal/ residue burning; however the scale depends on the quality and quantity of residues applied (Chivenge *et al.*, 2011). Parihar *et al.* (2020) found that CA practices registered 21% increase in water stable aggregates compared with CT at 0-15 cm soil depth. Adoption of CA results in C sequestration by virtue of enhancement in soil aggregation, and protection of C within aggregates (Du *et al.*, 2013; Shu *et al.*, 2015). Jiang *et al.* (2011) revealed that tillage significantly reduced the proportion of macro-aggregate fractions (>2.00 mm) and thus aggregate stability was reduced by 35% under CT compared with ZT. Large macro-aggregates, being the major storehouse of C, promoted C sequestration under ZT (Mazumdar *et al.*, 2015). Naresh *et al.* (2017) observed that macro-aggregates are less stable than micro-aggregates and more susceptible to the disruptive forces of tillage, and > 2 mm size macroaggregates showed the lowest percentage distribution across depths. This might be attributed to the mechanical disruption of macro-aggregates with frequent tillage operations and reduced aggregate stability. However, formation of micro-aggregates within macro-aggregates can play an important role in C storage and stabilization in the long term (Hati *et al.*, 2021).

2.6 Impacts of long-term conservation agricultural practices on organic C stabilization within structural soil aggregates

Tisdall and Oades (1982) proposed that microaggregates are formed free and gradually become macroaggregate constituents, but Oades (1984) reported that C is first assimilated in macroaggregates and then forms microaggregate nuclei. Physical stabilisation of C is estimated by measuring the free light fraction (LF), intra-aggregate POM (iPOM), and mineral-associated fractions (Six *et al.*, 1999). Golchin *et al.* (1994) suggested that quality and types of CR affect the free LF. Fine iPOM C from macroaggregates was two to three times higher in ZT than CT at all three sites. No significant difference was observed in coarse iPOM_C due to tillage, and similar results were obtained in microaggregate iPOM_C. A long-term experiment in Calcisol, Aragon, NE Spain showed that mineral-associated OM fraction outside and within microaggregates constituted 54 and 26% of total SOC and was not

affected by tillage management (Blanco-Moure *et al.*, 2016). They also found a strong correlation between microaggregates' mineral fraction and stable microaggregates, indicating that physical protection is a major form of soil C stabilisation. The cPOM-C and iPOM-C were sensitive to tillage and were higher in ZT than CT.

Clay and silt fractions chemically stabilise SOM by the virtue of high surface area, in turn physically stabilizing SOM within microaggregates (Six *et al.*, 2001). The CT causes a decrease in SOC due to loss of POM C in sandy soil and clay-associated C in clayey soil, (Feller and Beare, 1997). The mechanisms of physical C stabilization in tropical and sub-tropical soils are less studied, and needs to be explored in detail.

2.7 Impacts of long-term conservation agricultural practices on glomalin content

About 80% of all plant species on land are associated with fungus called arbuscular mycorrhizal (AM) fungi, which develop mutualistic symbiotic partnerships and make inaccessible soil nutrients available to the plant (Kottke and Nebel, 2005). When a plant and a fungus form a symbiotic relationship, the fungus gains access to photosynthetic carbohydrates through the host plant's arbuscules, an intracellular fungal organ that acts as an exchange site (Wilkes *et al.*, 2020; Wright *et al.*, 1996). Along their mycelial network, AM fungus synthesises glycoprotein glomalin as a structural support molecule (Driver *et al.*, 2005). Lovelock *et al.* (2004) defined glomalin as a glue-like sticky substance with the capacity to bind soil particles. Soil aggregate stability and SOC storage are two environmental parameters that AM fungi contribute through the plant–fungi connection (Begum *et al.*, 2019). Additionally, glomalin stores C (~ 20-30%) and nitrogen (N) (~ 3-5%) in soils for an extended period of time (Lovelock *et al.*, 2004). Glomalin produced by AM fungi plays a key role in the sequestration of carbon dioxide from the atmosphere. Carbon dioxide (CO₂) intake and photosynthesis are boosted by AM fungus growth stimulation, which in turn raises fungal biomass and glomalin (Rillig *et al.*, 2002). Due to glomalin's poorly defined structure, glomalin-related soil proteins (GRSP) are reported instead of pure glomalin (Schindler *et al.*, 2007).

Agricultural management practices alter glomalin by influencing biological activity (Dick, 1992). The CA practices increase glomalin protein compared to CT (Avio *et al.*, 2013; Sharma *et al.*, 2019). Soil ploughing inhibits root colonization and nutrient absorption by disrupting AMF hyphal networks (Kabir, 2005). Soil inversion might release soil accumulated C back into the atmosphere. The CT breaks apart fungal mycelia, degrading hyphal structures that regulate soil glomalin concentrations, lowering glomalin production in

CT soils and increasing soil erosion (Mathew *et al.*, 2012; Wilkes *et al.*, 2021). Singh *et al.* (2017) found that the CR-retained plots exhibited more soil glomalin than no residue. CA had more glomalin than CT (Bhattacharya *et al.*, 2020a). The CA systems are related with increased AMF diversity and functioning, whereas CT systems, employed to increase crop output, significantly affect AMF diversity and functioning (Castillo *et al.*, 2006), lowering soil glomalin.

2.8 Impacts of long-term conservation agricultural practices on soil organic carbon mineralization and its temperature sensitivity

The balance between carbon (C) inputs and outputs arising from SOC mineralization largely determines the amount of SOC that accumulates in soil. As a consequence, raising C stocks may be achieved by lowering the amount of SOC mineralization. The warming of the atmosphere acts as positive feedback for climate change (IPCC, 2013), accelerating the breakdown of SOC stocks *via* enhanced microbial respiration and, as a consequence, greater release of SOC to the atmosphere (Davidson and Janssens, 2006).

The SOC mineralization rate increases by 10 °C as a result of temperature sensitivity (Q_{10}) (Fang and Moncrieff, 2001). According to numerous studies, the values of Q_{10} changes considerably throughout a broad temperature spectrum (Ghosh *et al.*, 2016, 2018). In a broad sense, rising ambient temperatures hastened the rate at which SOC was mineralized (Parihar *et al.*, 2019; Qin *et al.*, 2019). At higher temperatures, solubility and transport of C substrate into active sites of enzymes gets elevated and in turn more quantity of substrate gets accessible for microbial degradation (Davidson *et al.*, 2012). Increasing the temperature of SOM-humate complexes, which are generally resistant, has also been shown to facilitate desorption (Davidson and Janssens, 2006). This reduces physical protection and promotes SOM disintegration (Conant *et al.*, 2011; Schmidt *et al.*, 2011). High temperatures easily dissolve waxes and lipids from dead microorganism cell membranes that were previously resistant to disintegration (Davidson and Janssens, 2006). Temperature sensitivity rises with the SOM's "recalcitrance," as predicted by Arrhenius' kinetic theory (Davidson and Janssens, 2006). According to Huang *et al.* (2021), higher temperature considerably enhanced the maize residue breakdown by boosting decomposition rate and changing some of the more resistant carbon into more readily available carbon. It was shown that maize residue and SOC breakdown was more sensitive to temperature at 15 – 25 °C than at 25–35 °C. On the contrary, Giardina and Ryan (2000) reported non-significant effects of temperature variations on recalcitrant C. In another study, Conen *et al.* (2006) reported similar temperature

sensitivity of labile and non-labile SOC. The Q_{10} is closely related to activation energy (a measure of the energy required for decomposers to reach the material) (Alekseyeva *et al.*, 2022) deduced that a high Q_{10} value (>2) is due to a conformational change in proteins and indicates the need for high activation energy.

The CA has a considerable influence on the decay rates and Q_{10} of carbon mineralization by virtue of alteration of soil aggregates, microbial diversity and adaption, as well as moisture and temperature regimes within the soil (Jat *et al.*, 2019). The quantity and type of CR affected the bio-chemical make-up of SOM, affecting their chemical stability against increasing temperatures (Dey *et al.*, 2018). Datta *et al.* (2019) studied the C mineralization modified by residue location, type and interactions. Rice residue decomposed faster than wheat and maize regardless of positioning. Rice and wheat decomposed faster when incorporated than when applied on the surface. The contribution of each residue type to C mineralization of the combination was additive. Mungbean residue fed to rice/wheat or maize/wheat increased residue breakdown. Crop residues with low N and high C/N ratios, such as maize, wheat, rice and their combinations, may be placed on the soil surface for quicker C and N mineralization. Kan *et al.* (2020a) reported that maize CR boosted SOC mineralization but lowered its Q_{10} compared to wheat CR. Macro-aggregates exhibited greater Q_{10} values than micro-aggregates in the wheat and maize seasons, respectively (Kan *et al.*, 2020a). Rakesh *et al.* (2021) found that residue incorporation into the soil increased C footprints by maximizing C mineralization than surface applied residues, irrespective of the type of residue. Kan *et al.* (2020b) showed that ZT had less basal mineralization than CT irrespective of residue management. Studies conducted by Yuan *et al.* (2022) revealed that soil microbial abundance was positively correlated with soil respiration (SR) and negatively correlated with Q_{10} . Jat *et al.* (2019) found that cumulative C mineralization were significantly higher under PB with CR retention, but with a lower decay rate (K_c) compared with PB without CR retention. Parihar *et al.* (2019) reported that SOC at 7.5-15 and 15-30 cm was 1.3 and 2.1 times more temperature sensitive than that at surface soil (0–7.5 cm) under CA.

3. MATERIALS AND METHODS

In order to address the objectives of the investigation entitled “**SOIL ORGANIC CARBON DYNAMICS UNDER CONSERVATION AGRICULTURE BASED MAIZE-MUSTARD SYSTEM IN AN INCEPTISOL**” soil samples were collected from ongoing conservation agriculture based field experiment at ICAR-Indian Agricultural Research Institute (IARI), New Delhi under maize-mustard system. Detailed description of the materials used and methods deployed during the course of investigation is furnished below:

Table 3.1. Initial soil characteristics at the onset of the field experiment during kharif 2010

Climatic parameters	
Maximum temperature in summer (°C)	40 to 44
Minimum temperature in winter (°C)	3 to 8
Mean annual rainfall (mm)	900
Wind velocity throughout the year (km h ⁻¹)	3.5 to 4.3
Soil parameters	
Taxonomical classification	Typic Haplaquept
Texture	Sandy clay loam
pH	7.9
Walkley-Black carbon (g kg ⁻¹)	5.4
Bulk density (Mg m ⁻³)	1.50

3.1. General information about experimental site

3.1.1. Location and climate

The experiment was conducted at the ICAR-IARI, which is located at 28°35'N, 77°12'E, and 229 m above mean sea level. The region is part of the Indo-Gangetic Plain region's Upper-Gangetic Plain transects, which is characterized by automated and input-intensive agriculture. According to the categorization of the National Bureau of Soil Survey and Land Use Planning (NBSS & LUP), the experimental site represents Agro-ecological sub-region 4.1 *i.e.* North Punjab Plain, Ganga-Yamuna Doab and Rajasthan upland, hot and dry semi-arid eco-sub region. New Delhi's climate is subtropical with dry, scorching summers and bitterly cold winters separated by a three-month monsoon season. The warmest

month is May, while the coolest is January. Long-term weather data indicated a mean maximum temperature of 32.1°C, a mean minimum temperature of 17°C, and an average rainfall of 788 mm. More than three-fourth of the total rainfall is received through south-west monsoon during July to September.

3.1.2. Soil characterization

The soil of the experimental site is of Gangetic alluvial origin, very deep (> 2 m), well-drained, and of flat to gently sloping topography. Taxonomically, it is classified as Typic Haplaquept. Important soil characteristics at the onset of the field experiment during 2010 are given in Table 3.1. Apparently, the sandy clay loam soil was mildly alkaline in reaction, non-saline, medium in organic carbon, and medium in available P (Olsen-P) and available K content.

3.2. Layout and experimental details

The field experiment on maize (*Zea mays* L.)-mustard (*Brassica juncea* L.) cropping system commenced in monsoon 2010 at ICAR-IARI research farm 14B as a part of the Conservation Agriculture project IARI, layout of which is given in Fig. 3.1. In the first three years (2010-11 to 2012-13), rice-maize cropping system was followed. The system was changed to rice-mustard system from 2013-14 onwards as winter maize (*Zea mays*) was very much susceptible to frost damage under this region, and then continued for five years till 2017-18. Due to allelopathy effect of mustard on rice crop, the rice-mustard system was changed to maize-mustard system which is still being continued. Seven treatments were evaluated in a randomized block design, comprising three double cropping ZT and two triple cropping ZT systems with or without crops residue retention along with two conventional till systems (control) with three replications. Treatments details are furnished below:

- **T₁:** Zero till maize–Zero till mustard: ZTMz(-R)–ZTM(-R)
- **T₂:** Mustard residue in Zero till maize–Maize residue in Zero till mustard: ZTMz+R–ZTM+R
- **T₃:** Mustard residue in Zero till maize with brown manuring – Maize residue in Zero till mustard: ZTMz+R+BM–ZTM+R
- **T₄:** Zero till maize–Zero till mustard–Zero till summer mungbean: ZTMz(-R)–ZTM(-R)–ZTMB(-R)

- **T₅:** Mungbean residue in Zero till maize–Maize residue in Zero till mustard–Mustard residue in Zero till summer mungbean: ZTMz+R–ZTM+R–ZTMB+R
- **T₆:** Conventional till maize–Zero till mustard: CTMz(-R)–ZTM(-R)
- **T₇:** Conventional till maize–Conventional till mustard: CTMz–CTM

Soil test-based recommended N-P-K rates were 150-60-40 kg ha⁻¹ for maize and 80-60-40 kg ha⁻¹ for mustard, which were applied through urea, diammonium phosphate (DAP) and muriate of potash (MoP), respectively, whereas 100 kg ha⁻¹ DAP was applied for the mungbean crop. Entire amount of P and K was applied as basal in both maize and mustard, whereas N was applied in three equal splits of 33% each at basal, knee height stage and tasseling stage of maize, respectively. Maize (cv. PMH1) was sown in the first week of July and harvested on 18th of October. Subsequent mustard (cv. PM25) was sown on 3rd November and harvested on 8th March followed by summer mungbean (SML832) sowing. Maize, mustard and mungbean were sown using a turbo seeder with 18, 4–5 and 18 kg seed ha⁻¹, respectively. Maize, mustard and mungbean were sown at 60, 40, 20 cm rows spacing respectively. Maize was harvested manually and the mustard crop was harvested by mustard thresher. In case of maize, ~50% residue retention was considered, whereas 40% and 100% crop residue retention was considered in mustard and mungbean, respectively. For brown manuring practice, *Sesbania aculeata* (broadcasted) were sown on the same day of maize sowing, grown together as co-culture, and then *Sesbania* plants were killed at 25 DAS by applying 2,4-D at 0.5 kg a.i. ha⁻¹ (Sen *et al.*, 2021). Crops were raised under assured irrigated condition such that for the maize crop, 4-5 irrigations, for mustard crop, 2–4 irrigations and for mungbean, 2–3 irrigations were given, depending on the frequency and intensity of rainfall received during the crop growing period (Das *et al.*, 2020). Prescribed weed and pest control measure were adopted as pre-emergence, post-emergence herbicide application and insecticide application as well as seed treatment, respectively. Plot size was 42.5 m × 8 m with plot area of 340 m².

3.3. Soil sampling and processing

Soil samples (0–5 and 5–15 cm) from replicated plots of treatments were collected after the harvest of maize in 2021. Freshly collected field-moist soil samples were divided into three parts, one part was kept in refrigerator at 4°C for analysis of biological parameters, the second part was kept for aggregate analysis and the remaining portion was air dried, ground in wooden mortar and pestle, and sieved to pass through a 2 mm sieve for analysis of

different soil parameters. The moisture content was determined immediately by gravimetric method (Black, 1965).

3.4. Soil analysis

3.4.1. Soil reaction (pH) and electrical conductivity

The pH of soil samples was determined in 1:2.5 soil: water suspension by a digital pH meter using combined electrode. The electrical conductivity (EC) was determined in the supernatant of the same soil: water ratio with the help of a conductivity bridge and expressed as dS m⁻¹ at 25 °C (Jackson, 1973).

3.4.2. Bulk density

Soil bulk density was calculated using a cylindrical core sampler. A core sampler made up of galvanized iron cylinder of 5 cm diameter and 5.9 cm height was driven into the soil to a desired depth. The extra soil of the core was trimmed off from both sides with a spatula or sharp knife and the soil in the core was transferred to an aluminium can carefully. Then it was put in the oven and dried at 105°C till constant weight was achieved. After that, the cans were taken out and bulk density of the soil was calculated by the formula (Veihmeyer and Hendrickson, 1948):

$$\text{Bulk density (Mg m}^{-3}\text{)} = [\text{weight of dry soil (Mg)}/\text{volume of the core (m}^3\text{)}]$$

3.4.3. Soil aggregate separation

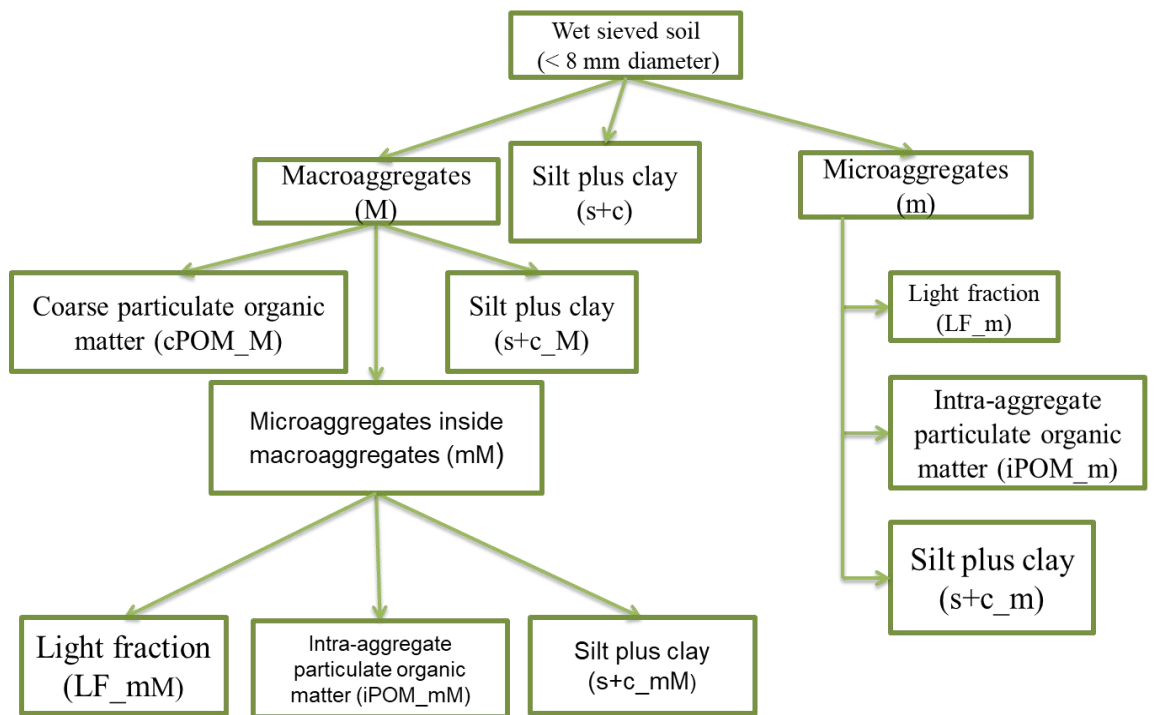
The larger clods were broken by hands into smaller segments along natural cleavage before air- drying the soil. The clods were passed through an 8 mm sieve. Then weighed 100g of this soil were placed in a sieve assembly comprised of 2 mm sieve on top followed by 250 µm and 53 µm sieve. This sieve assembly containing soil was dipped in water for 5 min to allow slaking in a Yoder's wet sieving apparatus. Thereafter the apparatus was run for 5-10 minutes. After wet-sieving, aggregates present on each sieve were transferred to a funnel containing a pre-weighed filter paper placed on the volumetric flask. The aggregates present on filter paper were air-dried followed by oven-drying at 40 °C until constant weight and finally weighed. Soil aggregation was calculated, and expressed as percentage. A sub-sample of aggregates was used for total C analysis. Aggregates retained on 250 µm sieve were considered as macro-aggregates (250-2000 µm) and aggregates retained on 53 µm sieve as micro-aggregates (53-250 µm) and the fraction (<53 µm) collected in the last box was silt + clay fraction (Yoder, 1936).

Mean weight diameter (MWD) was calculated from the following equation (Van Bavel, 1950): $MWD = \sum X_i \times W_i$

Where X_i was the mean diameter (mm) of the soil aggregate size fractions and W_i was the proportion of each aggregate size with respect to the total sample weight.

3.4.4. Density fractionation

The large and small macro aggregates obtained through wet-sieving were mixed together and 25g of this macro aggregates soil sample was placed on a 250 μ m sieve and again wet sieving was carried out. The fraction obtained are coarse particulate organic matter (c-POM_M, >250 μ m), micro-aggregate inside macro-aggregate (mM, 53-250 μ m) and silt + clay inside macro-aggregates (s+c_M, <53 μ m). The SOC was separated into light fraction (LF) and heavy fraction (HF) following the modified method described by Sohi *et al.* (2001) using sodium iodide (NaI) as presented in the flow chart (Fig 3.1)



Six *et al.*, (1998, 2002); Sohi *et al.*, (2001)

Fig 3.1. Fractionation scheme of macro and micro aggregates

Soil sample (5 g, macro-aggregate passed through a 250 μ m sieve and retained on a 53 μ m sieve during aggregate separation, mM) was taken in 50 mL plastic centrifuge tubes and NaI solution having density of 1.8 g cm⁻³ was added to it in 1:5 ratio. The mixture was hand shaken for 30 seconds and centrifuged for 1 h at 4,000 rpm. After that, the tubes were taken

out and the solution was decanted and filtered on a 47 mm diameter glass microfiber filter paper to separate the micro inside macro-aggregates LF (mM_LF). The weight of the mM_LF was taken after drying the previously weighed filter paper at 40 °C. The HF was washed (2-3 times) with distilled water to remove the NaI. Sodium hexa-metaphosphate (5%) was added to HF in 1:5 ratio and shaken for 18 h. The solution was then decanted in a 53 µm sieve to separate out the intra-particulate organic matter (i-POM_mM, > 53µm) and silt + clay fraction (s+c_mM) of microaggregate inside macroaggregates. Similar procedure was followed for separation of LF and HF from free microaggregates (m). The fraction obtained from this free microaggregate was m_LF, iPOM_m and s+c_m. The weights of all these fractions were taken separately after drying at 50 °C

3.4.5. Soil inorganic C

Total inorganic C of bulk soils was determined by titrimetric method (Jackson, 1973) using the following formula:

$$\text{Per cent CaCO}_3 = (B - A) \times (N \text{ of NaOH}) \times (50/10) \times 0.05 \times (100/W)$$

Where, B and A are volume of 0.25 N NaOH consumed in blank and sample titration, N = Normality of NaOH, W = Weight of sample in gram.

3.4.6. Total soil carbon

The bulk soils as well as aggregates were ground and passed through a 0.2-mm sieve and kept in oven for 24 hours at 40 °C prior to determination of total C. Total carbon (TC) was determined by dry combustion method using a CHNS Analyzer (EuroVector Instruments, EA 3000, Italy) (Nelson and Sommers, 1982).

3.4.7. Total soil organic C (SOC)

Total SOC of bulk soils as well as aggregates was calculated by subtracting soil inorganic C concentrations from total C concentrations

Soil organic carbon stock

It was calculated using the given formula:

$$\text{C stock (Mg ha}^{-1}\text{)} = [\text{Total SOC (\%)/100}] \times \text{bulk density (Mg m}^{-3}\text{)} \times \text{depth (m)} \times 10,000 \text{ (m}^2\text{ ha}^{-1}\text{)}.$$

3.4.8. Soil organic carbon

The easily oxidizable organic carbon content in soil was determined by wet oxidation

method of Walkley and Black (1934).

3.4.9. Soil organic carbon pools of varying oxidizability

Different fractions of oxidizable SOC were determined using modified Walkley-Black method, as described by Chan *et al.* (2001). 0.5 g of soil sample was taken in a 500 mL conical flask and 10 mL of 1N K₂Cr₂O₇ was added to each flask, followed by addition of 10 and 20 mL of concentrated H₂SO₄ corresponding to 18 N and 24 N of H₂SO₄, respectively. The flasks were allowed to stand for 30 minutes. After 30 minutes, about 200 mL of distilled water was added, followed by titrating acid dichromate mixture against 0.5 N ferrous ammonium sulphate in the presence of diphenylamine indicator and concentrated H₃PO₄. Total SOC was divided into two fractions in order of decreasing oxidizability (Chan *et al.*, 2001):

Fraction 1 (CL-labile): organic carbon oxidizable with 18 N H₂SO₄

Fraction 2 (CNL-non-labile): residual OC after reaction with 18 N H₂SO₄ and subtracted with total SOC

3.4.10. Carbon cycling enzymes

Dehydrogenase activity

Dehydrogenase activity was determined following the method of Casida *et al.* (1964). 5 g soil was taken and mixed with 3% solution of 2,3,5-triphenyl tetrazolium chloride and 2.5 mL of distilled water, and incubated for 24 h at 37°C temperature in an incubator. After incubation, 10 mL methanol was added and shaken for 1 minute and filtered through a Whatman No.1 filter paper. The absorbance was measured at 485 nm by using a spectrophotometer.

β-glucosidase

β-glucosidase activity determination was based on colorimetric determination of the p-nitrophenol released by β-glucosidase when soil is incubated with buffered (pH 6.0) 4-Nitrophenyl β-D-glucopyranoside (PNG) solution and toluene (Tabatabai, 1982). 1 g soil was taken and 0.2 mL toluene, 4 mL buffer (pH 6.0) and 1 mL PNG solution were added to it, and incubated for 1h at 37°C temperature. After incubation, 1 mL CaCl₂, 1 mL NaOH and 4 mL tris (hydroxymethyl) aminomethane (THAM) was added and filtered through a Whatman No.1 filter paper. The absorbance was measured at 420 nm using a spectrophotometer.

Phenol oxidase

Phenol oxidase activity was determined using phosphate solution containing catechol or proline (Perucci *et al.*, 2000). 1g soil was taken and 10 ml carbonate buffer was added, and the solution was homogenized. 2 ml supernatant was taken, and 2 ml 3-(3, 4-dihydroxyphenyl)-l-alanine (DOPA) solution was added to it, and incubated in dark for one hour. The absorbance was measured at 460 nm using a spectrophotometer.

3.4.11. Soil microbial biomass carbon

Soil microbial biomass carbon (MBC) was estimated using chloroform fumigation extraction method (Jenkinson and Powlson, 1976) in field-moist soil samples using the following formula:

$$MBC = (OC_F - OC_{UF}) / K_{EC}$$

Where, OC_F = organic carbon extracted from fumigated and OC_{UF} = organic carbon extracted from un-fumigated soil (result expressed on oven dry basis), and K_{EC} = extraction efficiency. Generally a K_{EC} value of 0.45 was considered as a value for microbial extraction efficiency and therefore was used for the calculation.

3.4.12. Glomalin

In 50 mL autoclavable polypropylene tubes, one gram of air-dried soil was taken, and 8 mL of a 20 mM citrate solution, adjusted to a pH of 8, was added. Two minutes of vortexes and a 90-minute autoclave at 121 °C removed the glomalin. The supernatant from autoclaved tubes was collected after they were centrifuged for 10 minutes at 5000 rpm. The supernatant was refrigerated until analysis. To eliminate glomalin (red-brown pigment), the supernatant was centrifuged until it was straw coloured. 1 mL of total extracted supernatant was transferred to microtiter tubes with 1 mL Bradford dye (50:50). The measurements were made at 590 nm. The study's standard was bovine serine albumin (BSA) (Wright and Upadhyaya, 1996).

3.4.13. Soil organic carbon mineralization

For carbon mineralization studies, samples of bulk soils from the same 7 treatments, from depth 0-5 cm, were placed at two temperatures (27°C and 37°C) in laboratory incubators for 32 days. For this, 40 g undisturbed moist soil (dry weight basis) from each treatment in three replicates was weighed in individual 500 mL conical flasks. Empty conical flasks with alkali trap (vial containing 4 mL of 0.5 N NaOH) were kept as blanks in respective studies. In each sample, water was maintained at 70% water holding capacity with alkali trap (vial containing 4 mL of 0.5 N NaOH) and the flasks were air tightened. Prior to this, the soil samples were

pre-incubated for two weeks at 25 °C that helped to discard “pulsing effect”. The CO₂ was trapped in 4 mL 0.5 N NaOH. The rate of CO₂ production of the soil samples was measured at 0, 2, 4, 8, 16 and 32 days of the incubation. The amount of CO₂ trapped were determined by back titration of the excess 0.5 N NaOH with 0.5 N HCl. Prior to that saturated BaCl₂ (so as to convert Na₂CO₃ to BaCO₃) was added followed by phenolphthalein indicator. At each sampling date, flasks were kept open meanwhile titration duration to facilitate O₂ supply after removal of NaOH. The C mineralization was calculated through following formula:

$$\text{C mineralized (mg 100 g}^{-1}\text{ soil)} = \{(B-A) \times N \times 6 \times 100\} / W$$

Where B and A are the volume (mL) of HCl consumed for titrating 4 mL 0.5 N NaOH in control (flask without soil) and soil, N is the normality of HCl and 6 is the equivalent weight of C. Cumulative C mineralization (C_t) was computed by summing up the C mineralization at different days of observation.

An exponential model (Stanford and Smith, 1972) was used to determine C loss with time:

$$C_t = C_o (1 - e^{-K_c t})$$

Where C_o represents the potentially mineralisable SOC, C_t represents the cumulative C mineralized at time t, and K_c represents decay rate SOC mineralization.

The temperature sensitivity of soil respiration is expressed as the Van't Hoff's temperature coefficient Q₁₀, which describes the factor by which the rate increases with a 10°C rise in temperature, and was calculated using the following formula (Janssens and Pilegaard, 2003):

$$Q_{10} = (\text{Rate of C mineralization at } 37^\circ\text{C} / \text{Rate of C mineralization at } 27^\circ\text{C})^{(10/T-T)}$$

Where, T₂ and T₁ are 37 °C and 27 °C respectively.

Here rate of mineralization means, the K_c value obtained from Stanford and Smith (1972) equation at respective temperatures which is the decay rate at T degree temperature (K), A is a pre-exponential factor which indicates decay rate when T → ∞. Activation energy refers to the minimum amount of energy required by the participating molecules in order to undergo a specified reaction.

3.4.14. Statistical analysis:

Correlation and regression analysis will be done among the different variables. Two-way analysis of variance (ANOVA) and Post hoc analysis also carried out to compare the

mean of different treatments. All the statistical analyses of the data was carried out following the procedures suggested by Gomez and Gomez (1984) using R statistical software package.

4. RESULTS

The results obtained in the present investigation on the impacts of long-term conservation agricultural practices on carbon pools, carbon cycling enzymes, its stock and carbon stabilization within soil aggregates, carbon mineralization and its temperature sensitivity and other related parameters are presented in this chapter.

4.1 Effect of conservation agriculture on soil physico-chemical properties

4.1.1 pH and Electrical Conductivity

The effects of tillage and residue management on soil pH and EC in the surface (0-5 cm) and subsurface (5-15 cm) depths are presented in Table 4.1. For surface (0–5 cm) and subsurface (5–15 cm) soil layers, the pH of the experimental soil varied from 8.19 to 8.23 on the surface and from 8.22 to 8.34 on the subsurface soil. However, there is no significant differences among the treatments.

Table: 4.1 Effect of conservation agriculture on soil pH and electrical conductivity under the

Treatments	pH		EC	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	8.21 ^a	8.34 ^a	0.21 ^a	0.23 ^a
T ₂ : ZTMz+R–ZTM+R	8.20 ^a	8.25 ^a	0.20 ^a	0.22 ^a
T ₃ : ZTMz+R+BM–ZTM+R	8.20 ^a	8.22 ^a	0.20 ^a	0.24 ^a
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	8.23 ^a	8.33 ^a	0.22 ^a	0.24 ^a
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	8.21 ^a	8.34 ^a	0.23 ^a	0.26 ^a
T ₆ : CTMz(-R)–ZTM(-R)	8.19 ^a	8.23 ^a	0.21 ^a	0.26 ^a
T ₇ : CTMz–CTM	8.19 ^a	8.24 ^a	0.23 ^a	0.24 ^a
LSD (P<0.05)	NS	NS	NS	NS

maize-mustard system in an Inceptisol

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

Electrical conductivity (EC) of the soil had no significant difference among different treatments. From the Table 4.1, the data show that subsurface soil (5–15 cm) had more EC

compared with surface soil (0–5 cm). The EC of surface soil ranged from 0.20 dS m⁻¹ to 0.23 dS m⁻¹, whereas in the subsurface it was from 0.22 to 0.26 dS m⁻¹.

4.1.2 Bulk density (Mg m⁻³)

Tillage and residue management practices had significant effect on soil bulk density (BD) at 0–5 cm depth but not in 5–15 cm depth (Table 4.2). In the 0-5 cm depth, the highest BD was recorded in ZTMz+R–ZTM+R–ZTMB+R and ZTMz+R+BM–ZTM+R treatments (1.39 Mg m⁻³) which was also at par with different ZT with or without residue management treatments and 3.73% higher than CTMz-CTM (1.34 Mg m⁻³) conventional management treatment. The bulk density in the subsurface (5–15 cm) soil layer varied from 1.54 –1.57 Mg m⁻³ and did not show any significant differences.

Table: 4.2 Effect of 11 years conservation agriculture on soil bulk density (Mg m⁻³) under the maize-mustard system in an Inceptisol

Treatments	BD (Mg m ⁻³)	
	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	1.37 ^{abc}	1.56 ^a
T ₂ : ZTMz+R–ZTM+R	1.38 ^{abc}	1.55 ^a
T ₃ : ZTMz+R+BM–ZTM+R	1.39 ^a	1.56 ^a
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	1.37 ^{abc}	1.55 ^a
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	1.39 ^a	1.57 ^a
T ₆ : CTMz(-R)–ZTM(-R)	1.35 ^{bc}	1.54 ^a
T ₇ : CTMz–CTM	1.34 ^c	1.54 ^a
LSD (P<0.05)	0.04	NS

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.1.3 Total carbon (TC), Total inorganic carbon (TIC) and Total organic carbon (TOC) (g kg⁻¹) in bulk soil

Data pertaining to total carbon (TC), total inorganic carbon (TIC) and total organic carbon (TOC) at two different depths (0-5 and 5-15 cm) are given in Table 4.3. TC and TOC (g kg⁻¹) concentrations were significantly affected by different tillage and residue management practices under both soil depths, while the effect was non-significant on TIC (g

kg⁻¹) concentration. TC and TOC (g kg⁻¹) concentrations were always higher in the 0-5 cm depth than 5-15 cm. The highest TC concentration (10.61 g kg⁻¹) was recorded in ZTMz+R–ZTM+R–ZTMB+R treatment which was at par with ZTMz(-R)–ZTM(-R)–ZTMB(-R) treatment and 11.68% higher than CTMz-CTM treatment (lowest TC concentration) in the 0-5 cm soil layer. In the 5-15 cm soil layer the TC concentration ranged from 9.21 (CTMz-CTM) to 10.26 g kg⁻¹ ZTMz+R–ZTM+R–ZTMB+R. ZTMz+R–ZTM+R–ZTMB+R treatment also showed significantly higher TC concentration than rest of the treatments.

Total organic carbon showed similar result as of TC, where T₅ treatment showed significantly highest values of 9.29 and 8.74 (g kg⁻¹), respectively, at 0-5 and 5-15 cm, which was 13.15 and 13.35 % over the T₇. In TIC (g kg⁻¹) contradiction showed no significant difference among the treatments.

However, total inorganic carbon (TIC) (g kg⁻¹) concentration was not significantly affected by conservation agricultural practices in the 0-5 cm and 5-15 cm soil layers (Table 4.3)

4.3 Effect of 11-years of conservation agriculture under a maize-mustard system on total carbon (TC), total inorganic carbon (TIC) and total organic carbon (TOC) (g kg⁻¹) of bulk soil in an Inceptisol.

Treatments	TC (g kg ⁻¹)		TIC (g kg ⁻¹)		TOC (g kg ⁻¹)	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	9.67 ^{bc}	9.25 ^d	1.28 ^a	1.44 ^a	8.39 ^{bc}	7.81 ^{de}
T ₂ : ZTMz+R–ZTM+R	9.77 ^{bc}	9.42 ^c	1.30 ^a	1.51 ^a	8.46 ^{bc}	7.91 ^{cd}
T ₃ : ZTMz+R+BM–ZTM+R	9.77 ^{bc}	9.62 ^b	1.35 ^a	1.48 ^a	8.42 ^{bc}	8.15 ^b
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	10.2 ^{ab}	9.46 ^c	1.30 ^a	1.45 ^a	8.84 ^{bc}	8.00 ^c
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	10.6 ^a	10.3 ^a	1.32 ^a	1.52 ^a	9.29 ^a	8.74 ^a
T ₆ : CTMz(-R)–ZTM(-R)	9.6 ^{bc}	9.30 ^d	1.31 ^a	1.50 ^a	8.30 ^{bc}	7.72 ^e
T ₇ : CTMz–CTM	9.50 ^c	9.21 ^d	1.29 ^a	1.50 ^a	8.21 ^c	7.71 ^e
LSD (P<0.05)	0.59	0.05	NS	NS	0.63	0.10

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.1.4 Carbon pools in bulk soil (g kg⁻¹)

The effect of conservation agriculture with different tillage and residue retention treatments on carbon pools (labile and recalcitrant) is given in Table 4.4. The results showed that the treatment T₅ had increased levels of labile carbon (g kg⁻¹) at both the depths (4.51 and 3.03 g kg⁻¹). At 0-5 and 5-15 cm depths, it recorded 59.92 and 50.74% labile carbon higher than T₇ treatment. The lowest amounts of labile carbon (2.82 and 2.01 g kg⁻¹ at 0-5 and 5-15 cm, respectively) were recorded in T₇ treatment.

The recalcitrant carbon pools increased with increase in soil depth. The highest (5.31 g kg⁻¹) recalcitrant carbon pool was found in T₄ treatment, which was at par with T₁, T₂ and T₃ treatments at 0-5 cm depth. In case of 5-15 cm depth, the highest (6.79 g kg⁻¹) recalcitrant carbon pool was found in T₆ treatment with all other treatments being at par except T₄ and T₅. The lowest recalcitrant carbon pools (4.63 and 5.67 g kg⁻¹, respectively) were recorded under T₅ treatment at 0-5 and 5-15 cm depths.

4.4 Effect of 11-years of conservation agriculture under a maize-mustard system on soil carbon pools (g kg⁻¹) of bulk soil in an Inceptisol

Treatment	Labile carbon (g kg ⁻¹)		Recalcitrant carbon (g kg ⁻¹)	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	2.82 ^{cd}	2.03 ^b	5.41 ^a	6.55 ^a
T ₂ : ZTMz+R–ZTM+R	3.34 ^{bc}	2.17 ^b	5.23 ^{ab}	6.53 ^a
T ₃ : ZTMz+R+BM–ZTM+R	3.73 ^b	2.85 ^a	5.24 ^{abc}	6.57 ^a
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	3.54 ^b	2.91 ^a	5.31 ^a	6.00 ^b
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	4.51 ^a	3.03 ^a	4.63 ^d	5.67 ^b
T ₆ : CTMz(-R)–ZTM(-R)	2.84 ^d	2.03 ^b	5.02 ^{bc}	6.79 ^a
T ₇ : CTMz–CTM	2.82 ^d	2.01 ^b	4.90 ^c	6.59 ^a
LSD (P<0.05)	0.05	0.04	0.03	0.05

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.1.5 Soil microbial biomass carbon (SMBC) (mg kg⁻¹ dry soil) and glomalin (mg g⁻¹ soil)

The data pertaining to soil microbial biomass carbon (SMBC) and glomalin content after 11 years of conservation agriculture practices are presented in Table 4.5. The CA practices significantly affected the SMBC and glomalin content. The highest SMBC (647.93 and 339 mg kg⁻¹ dry soil at 0-5 and 5-15 cm, respectively) was recorded in T₅, which was 171 and 150 % higher than the T₇ treatment at their respective depths. The lowest SMBC under 0-

5 cm (238.57 mg kg⁻¹ dry soil) and 5-15 cm (135.60 mg kg⁻¹ dry soil) were found in T₇ and T₁ treatments, respectively.

Similarly, the highest glomalin contents (11.77 and 9.85 mg g⁻¹ soil at 0-5 and 5-15 cm, respectively) were recorded in T₅, which was 67.42 and 76.8 % more than T₇ treatment at their respective depths. T₅ treatment also had significantly higher glomalin content than the rest of the treatments at both the soil layers. The lowest glomalin content (7.03 and 5.07 mg g⁻¹ soil at 0-5 and 5-15 cm, respectively) was recorded in T₇ treatment.

4.5 Effect of 11-years of conservation agriculture under a maize-mustard system on Soil microbial biomass carbon (SMBC) (mg kg⁻¹ dry soil) and glomalin (mg g⁻¹ soil) in an Inceptisol

Treatment	SMBC (mg kg ⁻¹ dry soil)		Glomalin (mg g ⁻¹ soil)	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	443 ^d	136 ^d	9.33 ^{cd}	8.15 ^{cd}
T ₂ : ZTMz+R–ZTM+R	476 ^{cd}	204 ^c	9.45 ^{bcd}	8.13 ^{cd}
T ₃ : ZTMz+R+BM–ZTM+R	579 ^b	272 ^b	9.98 ^b	9.15 ^b
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	512 ^c	238 ^{bc}	9.68 ^{bc}	8.30 ^c
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	648 ^a	340 ^a	11.77 ^a	9.85 ^a
T ₆ : CTMz(-R)–ZTM(-R)	306 ^e	136 ^d	8.93 ^d	7.77 ^d
T ₇ : CTMz–CTM	239 ^f	136 ^d	7.03 ^e	5.57 ^e
LSD (P<0.05)	45	37	0.53	0.39

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.1.6 Mean weight diameter (MWD) (mm)

Conservation agricultural practices had a significant impact on the mean weight diameter (MWD) in both the soil layers (0–5 cm and the 5–15 cm) after 11 years of management practices (Table 4.6). The surface soil layer had higher MWD than the subsurface layer. The treatment T₅ had the highest MWD (0.77 and 0.64 mm at 0-5 and 5-15 cm depths, respectively), followed by T₄ (0.73 and 0.63 mm at 0-5 and 5-15 cm depths, respectively), and conventional tillage T₇ had the lowest MWD of 0.64 mm and 0.55 mm at 0-5 and 5-15 cm depths, respectively. T₅ treatment had significantly higher MWD i.e. 20.31 and 16.36 % more than the T₇ treatment at their respective depths. All the ZT with and

without residue treatments had significantly higher MWD than the partial ZT (T₆) and conventional tillage (T₇) treatments at 0-5 cm soil layer. Similar result was also found in case of 5-15 cm soil layer, except T₁ treatment.

Table: 4.6 The mean weight diameter and the percentage distribution of aggregates of bulk soil as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol.

Treatments	MWD (mm)		% Macro-aggregates		% Micro-aggregates	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	0.68 ^d	0.57 ^e	52.6 ^d	43.2 ^b	38.3 ^a	28.6 ^d
T ₂ : ZTMz+R–ZTM+R	0.71 ^c	0.58 ^d	54.2 ^{cd}	44.0 ^b	39.1 ^a	29.4 ^{cd}
T ₃ : ZTMz+R+BM–ZTM+R	0.71 ^c	0.61 ^c	56.1 ^{bc}	46.9 ^a	32.7 ^d	28.8 ^d
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	0.73 ^b	0.63 ^b	57.1 ^b	47.9 ^a	31.0 ^e	30.1 ^c
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	0.77 ^a	0.64 ^a	59.4 ^a	48.5 ^a	37.0 ^b	32.2 ^b
T ₆ : CTMz(-R)–ZTM(-R)	0.65 ^e	0.57 ^e	50.1 ^e	42.4 ^{bc}	34.7 ^c	33.6 ^a
T ₇ : CTMz–CTM	0.64 ^f	0.55 ^f	49.3 ^e	41.3 ^c	38.7 ^a	32.1 ^b
LSD (P<0.05)	0.01	0.01	1.9	1.7	1.2	0.8

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.1.7 Soil aggregation

Tables 4.6 shows the effect of tillage with various residue retentions on the depth-wise distribution of different aggregate sizes, namely macro and micro-aggregates. The results are discussed below:

a. Macro-aggregates

The macro-aggregate distribution of bulk soil is significantly affected by different tillage and residue management practices (Table 4.6). The percentage distribution of macro-aggregates is more in the surface soil layer (0–5 cm) compared to the subsurface (5–15 cm) layer, irrespective of the treatments. At 0-5 cm soil layer, the proportion of macro-aggregate was significantly higher (59.35 %) under T₅ treatment, which was 20.36 % higher than the conventional tillage, T₇ (49.31 %). Similarly, at 5-15 cm depth the proportion of macro-aggregate was significantly higher (48.49 %) under T₅ treatment, which was 17.32 % higher

than the conventional tillage, T₇ (41.33 %). However, at 5-15 cm depth, T₃ and T₄ treatments were found to be at par with the T₇ treatment.

b. Micro-aggregates

The percentage distribution of micro-aggregates of bulk soil as affected by 11-years of conservation agriculture is shown in Table 4.6. The micro-aggregates distribution significantly varied with different tillage and residue management practices. Overall, more proportion of micro-aggregates was found in surface soil layer (0-5 cm) than in subsurface soil layer (5-15 cm). At 0-5 cm depth, the highest micro-aggregate distribution was found in T₂ (39.12 %), followed by T₇ and T₁ treatments. Whereas, at 5-15 cm depth, the highest micro-aggregate distribution was found in T₆ (33.60 %) (CTMz-ZTM), followed by T₅ and T₇ treatments.

4.1.8 Aggregate associated carbon (g kg⁻¹)

a. Macro-aggregate associated carbon (g kg⁻¹)

The data pertaining to carbon (C) (g kg⁻¹) present in macro-aggregates (0-0.25 mm) at two different depths (0-5 and 5-15 cm) are given in Table 4.7. The result showed that macro-aggregate associated carbon affected significantly with respect to different tillage and residue retention under conservation agriculture irrespective of the depths. T₅ treatment showed significantly higher macro-aggregate associated C under both the depths (12.38 and 11.24 g kg⁻¹, respectively) than T₇ treatment which was also at par with T₃ and T₄ treatments. T₅ treatment also recorded 27.10 and 29.49 % higher macro-aggregate associated C concentration than T₇ at 0-5 and 5-15 cm depths, respectively. However, it was also noticed that macro-aggregate associated carbon decreased with increasing depth.

b. Micro-aggregate associated carbon (g kg⁻¹)

The carbon (C) (g kg⁻¹) present in micro-aggregates (0.25-0.053 mm) at two different depths (0-5 and 5-15 cm) is given in Table 4.7. The result showed that microaggregate associated C affected significantly with respect to different tillage and residue retention under conservation agriculture irrespective of the depths. T₅ showed significantly higher micro-aggregate associated C under both the depths (11.64 and 10.40 g kg⁻¹, respectively), which was also at par with T₄ treatment. T₅ treatment recorded 45.55 and 28.55 % higher micro-aggregate associated carbon than T₇ at 0-5 and 5-15 cm depths, respectively. However, it was also noticed that micro-aggregate associated carbon decreased with increasing depth.

Table: 4.7 The aggregate associated total carbon (g kg^{-1}) as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol.

Treatment	Macro-aggregates associated C (g kg^{-1})		Micro-aggregates associated C (g kg^{-1})	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	10.5 ^{bc}	9.34 ^c	9.49 ^{bc}	8.97 ^{cd}
T ₂ : ZTMz+R–ZTM+R	10.3 ^{bc}	9.67 ^{bc}	9.25 ^{cd}	8.88 ^{cd}
T ₃ : ZTMz+R+BM–ZTM+R	11.4 ^{ab}	10.6 ^{ab}	10.0 ^{bc}	9.33 ^{bc}
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	11.8 ^a	10.6 ^{ab}	10.6 ^{ab}	10.2 ^{ab}
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	12.4 ^a	11.2 ^a	11.6 ^a	10.4 ^a
T ₆ : CTMz(-R)–ZTM(-R)	10.2 ^c	9.20 ^c	8.20 ^e	8.4 ^{cd}
T ₇ : CTMz–CTM	9.74 ^c	8.70 ^c	8.00 ^e	8.09 ^d
LSD (P<0.05)	1.1	1.0	1.2	1.0

For each column, different letters indicate that the treatment means are significantly different at $P<0.05$ according to Tukey's HSD Test for separation of means

4.1.9 Aggregate associated carbon pools (g kg^{-1})

a. Macro-aggregate associated carbon pools (g kg^{-1})

The labile carbon (LC) and recalcitrant carbon (RC) (g kg^{-1}) present in macro-aggregates (0-0.25 mm) at two different depths (0-5 and 5-15 cm) are given in Table 4.8. The result showed that LC and RC were affected significantly with respect to different tillage and residue retention under conservation agriculture. Shallow depth of 0-5 cm always had higher LC and RC compared with 5-15 cm. At 0-5 cm, T₅ treatment showed significantly higher LC pool than the rest of the treatments, except T₄ and T₃ treatments. T₅ treatment recorded 120 % higher LC pool than T₇ treatment. At 5-15 cm depth, the highest LC (3.04 g kg^{-1}) pool was recorded with T₄ treatment which was also at par with T₅ treatment and significantly higher than rest of the treatments.

Similarly, macro-aggregate associated RC pool was recorded highest (5.45 g kg^{-1}) in T₅ treatment at 0-5 cm and 3.39 g kg^{-1} in T₄ treatment at 5-15 cm soil layer. The lowest macro-aggregate associated RC pool was recorded in T₁ treatment at both 0-5 cm and 5-15 cm soil layers.

Table: 4.8 The aggregate associated carbon pools (g kg^{-1}) as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol

Treatments	Macro-aggregates				Micro-aggregates			
	LC (g kg^{-1})		RC (g kg^{-1})		LC (g kg^{-1})		RC (g kg^{-1})	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	4.10 ^{cd}	1.03 ^d	3.81 ^b	1.19 ^d	2.78 ^d	2.83 ^c	4.36 ^a	5.49 ^{ab}
T ₂ : ZTMz+R–ZTM+R	4.55 ^{bcd}	2.21 ^c	3.59 ^b	2.42 ^{bc}	3.45 ^c	3.24 ^b	5.17 ^a	5.75 ^a
T ₃ : ZTMz+R+BM– ZTM+R	5.68 ^{abc}	2.46 ^b	4.51 ^{ab}	2.68 ^{ab}	3.82 ^{bc}	3.59 ^a	5.28 ^a	5.17 ^{abc}
T ₄ : ZTMz(-R)–ZTM(- R)–ZTMB(-R)	6.26 ^{ab}	3.04 ^a	5.01 ^a	3.39 ^a	3.99 ^b	3.56 ^a	4.87 ^a	5.13 ^{abc}
T ₅ : ZTMz+R–ZTM+R– ZTMB+R	7.41 ^a	2.84 ^a	5.45 ^a	2.93 ^{ab}	4.93 ^a	3.34 ^{ab}	5.34 ^a	4.61 ^{bc}
T ₆ : CTMz(-R)–ZTM(-R)	3.64 ^d	1.02 ^d	4.82 ^a	1.46 ^d	1.15 ^e	1.08 ^e	2.13 ^b	2.30 ^d
T ₇ : CTMz–CTM	3.37 ^d	1.07 ^d	4.82 ^a	1.68 ^{cd}	2.38 ^d	1.86 ^d	4.83 ^a	4.33 ^c
LSD (P<0.05)	1.95	0.23	1.01	0.95	0.44	0.26	1.01	0.96

For each column, different letters indicate that the treatment means are significantly different at $P<0.05$ according to Tukey's HSD Test for separation of means

b. Micro-aggregate associated carbon pools (g kg^{-1})

Similar to macro-aggregate C pools, micro-aggregate C pools also showed similar trend of different treatments influencing the labile and recalcitrant pools of carbon under conservation practice of various tillage and residue retention (Table 4.8). T₅ (ZTMz+R–ZTM+R–ZTMB+R) at 0-5 cm (4.93 g kg^{-1}) and T₃ at 5-15 cm (3.59 g kg^{-1}) showed highest LC pool in micro-aggregates. However, at 5-15 cm depth, T₃ and T₅ treatments were found at par with T₃ treatment. Comparing the depths, LC was higher in 0-5 cm than 5-15 cm depth. RC pool in micro-aggregates was also significantly affected by different treatments with T₅ (5.34 g kg^{-1}) and T₂ (5.75 g kg^{-1}) being the significantly highest values at 0-5 and 5-15 cm depths, respectively. At 0-5 cm depth, all treatments except T₆, recorded RC at par with the T₅ treatment, while at 5-15 cm depth, T₁, T₃ and T₄ were at par with T₂ treatment.

4.1.10 Dehydrogenase activity ($\mu\text{g TPF g}^{-1} \text{ day}^{-1}$) in bulk soil and within aggregates (macro and micro-aggregates)

The dehydrogenase activity after 11-years of cropping was significantly affected by tillage and residue management in topsoil (0-5 cm) and in the 5-15 cm soil depth (Table 4.9).

Within these two depths, 0-5 cm soil layer had higher dehydrogenase activity than the subsurface layer. The highest dehydrogenase activity in bulk soil was found in T₅ (ZTMz+R–ZTM+R–ZTMB+R) which was 28.65 % higher than T₇ (CTMz–CTM) treatment (lowest). The (ZTMz+R–ZTM+R–ZTMB+R) treatment also had similar DHA activity to ZTMz(–R)–ZTM(–R)–ZTMB(–R) treatment and was significantly higher than rest of the treatments. In general, dehydrogenase activity followed a similar trend in the 5-15 cm as that of the 0-5 cm soil layer. The highest DHA activity found in T₅ (ZTMz+R–ZTM+R–ZTMB+R) treatment (537.23 µg TPF g⁻¹ day⁻¹), whereas the lowest was found in CTMz–CTM treatment (354.42 µg TPF g⁻¹ day⁻¹).

Within the macro- and micro- aggregates, the DHA was significantly affected by the different treatments and it was found that T₅ treatment recorded significantly highest DHA in both micro- and macro-aggregates, irrespective of depths. Partial and complete conventional tillage systems (T₆ and T₇) always recorded lowest DHA. T₅ treatment had 69.21 and 25.80 % higher DHA activity in micro-aggregates than T₇ treatment.

Table 4.9 Dehydrogenase activity (µg TPF g⁻¹ day⁻¹) in bulk soil and within macro and micro aggregates as affected by 11- years of conservation agriculture under a maize-mustard system in an Inceptisol.

Treatments	Dehydrogenase activity (µg TPF g ⁻¹ day ⁻¹)					
	Bulk soil		Macro aggregates		Micro aggregates	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(–R)–ZTM(–R)	767 ^{bc}	387 ^{bc}	566 ^d	502 ^{bc}	491 ^b	378 ^{bc}
T ₂ : ZTMz+R–ZTM+R	800 ^b	423 ^b	597 ^{cd}	520 ^{bc}	548 ^{ab}	390 ^b
T ₃ : ZTMz+R+BM–ZTM+R	813 ^b	417 ^b	640 ^c	561 ^{abc}	571 ^{ab}	374 ^{bcd}
T ₄ : ZTMz(–R)–ZTM(–R)– ZTMB(–R)	881 ^a	407 ^b	717 ^b	645 ^{ab}	655 ^a	393 ^b
T ₅ : ZTMz+R–ZTM+R– ZTMB+R	910 ^a	537 ^a	774 ^a	711 ^a	708 ^a	429 ^a
T ₆ : CTMz(–R)–ZTM(–R)	726 ^{cd}	421 ^b	463 ^e	451 ^c	431 ^b	345 ^{cd}
T ₇ : CTMz–CTM	708 ^d	354 ^c	466 ^e	434 ^c	419 ^b	341 ^d
LSD (P<0.05)	54	46	46	165	160	35

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.1.11 β -glucosidase ($\mu\text{g p-nitro phenol g}^{-1} \text{ hr}^{-1}$) in bulk soil and within aggregates (macro and micro-aggregates)

Table 4.10 B-glucosidase ($\mu\text{g p-nitro phenol g}^{-1} \text{ hr}^{-1}$) in bulk soil, macroaggregate and microaggregate as affected by 11- years of conservation agriculture under a maize-mustard system in an Inceptisol.

Treatments	β -glucosidase ($\mu\text{g p-nitrophenol g}^{-1} \text{ hr}^{-1}$)					
	Bulk soil		Macro aggregates		Micro aggregates	
	0-5 cm	5-15 cm	0-5 cm	5-15 cm	0-5 cm	5-15 cm
T ₁ : ZTMz(-R)–ZTM(-R)	164 ^{cd}	109 ^b	65 ^c	57.0 ^d	69.0 ^{bc}	50.0 ^c
T ₂ : ZTMz+R–ZTM+R	191 ^{bc}	112 ^b	97 ^b	82.0 ^{bc}	83.0 ^{abc}	76.0 ^{abc}
T ₃ : ZTMz+R+BM– ZTM+R	210 ^{ab}	111 ^b	104 ^b	102 ^{ab}	104 ^{ab}	92.0 ^{ab}
T ₄ : ZTMz(-R)–ZTM(-R)– ZTMB(-R)	196 ^b	118 ^b	99.0 ^b	90.0 ^b	91.0 ^{abc}	70.0 ^{abc}
T ₅ : ZTMz+R–ZTM+R– ZTMB+R	234 ^a	136 ^a	130 ^a	115 ^a	120 ^a	107 ^a
T ₆ : CTMz(-R)–ZTM(-R)	145 ^{de}	81.0 ^c	70.0 ^c	63.0 ^{cd}	69.0 ^{bc}	56.0 ^{bc}
T ₇ : CTMz–CTM	124 ^e	78.0 ^c	63 ^c	53.0 ^d	55.0 ^c	48.0 ^c
LSD (P<0.05)	29.0	13.0	15.0	20.0	41.0	42.0

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

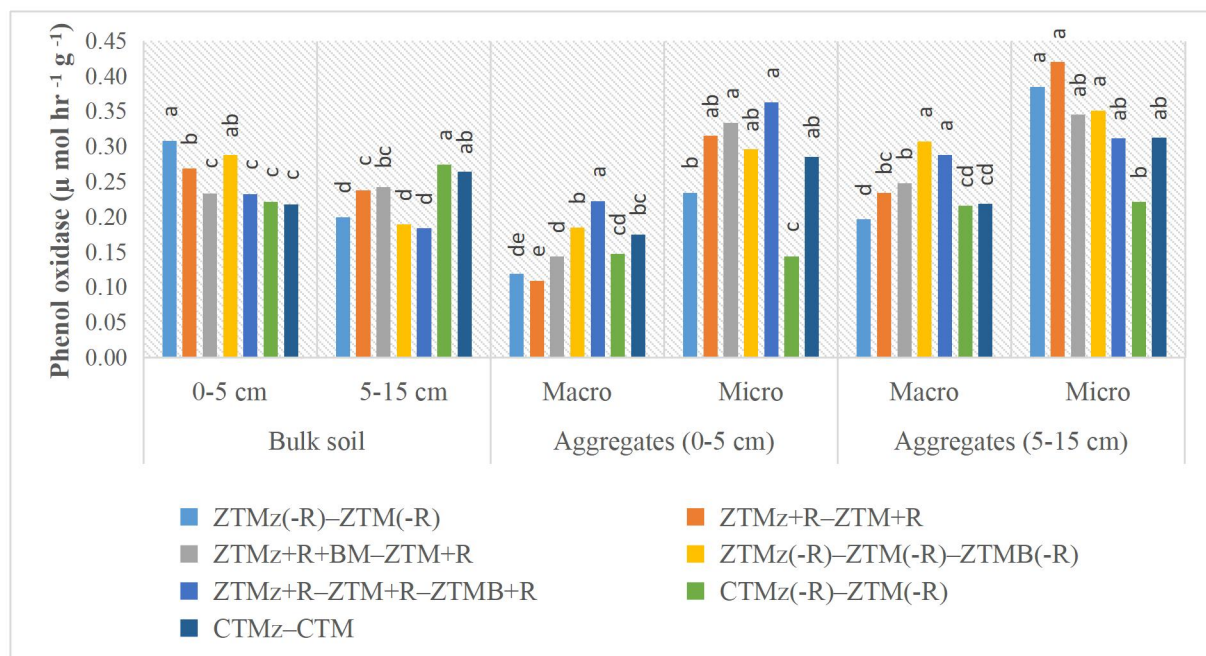
The β -glucosidase activity after 11-years of cropping was significantly affected by tillage and residue management in topsoil (0-5 cm) and in the 5-15 cm soil depth (Table 4.10). Within these two depths, 0-5 cm soil layer had higher β -glucosidase activity than the subsurface layer. The highest β -glucosidase activity in the bulk soil was found in T₅ (ZTMz+R–ZTM+R–ZTMB+R) (233.59 and 136.08 $\mu\text{g p-nitrophenol g}^{-1} \text{ hr}^{-1}$) which was 89.18 and 74.34 % higher at 0-5 and 5-15 cm depths, respectively, than T₇ (CTMz–CTM) treatment (lowest). T₅ treatment had β -glucosidase activity which was at par with T₃ treatment and significantly higher than rest of the treatments. At subsoil layer, the highest β -glucosidase activity was found in T₅ treatment (136.08 $\mu\text{g p-nitrophenol g}^{-1} \text{ hr}^{-1}$), whereas the lowest found in treatment (78.05 $\mu\text{g p-nitrophenol g}^{-1} \text{ hr}^{-1}$). Moreover, apart from T₅ treatment, rest of the ZT and with and without residue amended treatments showed similar result.

Within the macro- aggregates, the β -glucosidase activity was significantly affected by the different treatments and it was found that T_5 treatment recorded highest β -glucosidase activity within macro-aggregates irrespective of depths, whereas complete conventional tillage systems (T_7) recorded lowest β -glucosidase activity. T_5 also showed 105 and 116 % higher B-D glucosidase activity within macroaggregate when compared with T_7 treatment.

Similar trend was also observed in case of B-D glucosidase activity within microaggregate as of macroaggregate irrespective of the depth. The highest B-D glucosidase activity was recorded in microaggregate of T_5 treatment and lowest was found in microaggregate of T_7 treatment at both the depths.

4.1.12 Phenol oxidase ($\mu \text{ mol hr}^{-1} \text{ g}^{-1}$) in bulk soil and within aggregates (macro and micro-aggregates)

The phenol oxidase ($\mu \text{ mol hr}^{-1} \text{ g}^{-1}$) in bulk soil after 11-years of cropping was significantly affected by tillage and residue management in topsoil (0-5 cm) and in the 5-15 cm soil depth (Fig 4.1). Within these two depths, 0-5 cm soil layer had higher phenol oxidase activity than the subsurface layer under different zero tillage systems than conventional tillage and vice-versa at 5-15 cm depth in the bulk soil. The highest phenol oxidase activity was in T_1 ZTMz(-R)–ZTM(-R) which was 41.28 % higher than T_7 (CTMz-CTM) treatment (lowest) at 0-5 cm soil layer.



Bars with similar lowercase letters are not significantly different at $p < 0.05$ according to Tukey's HSD test

Figure 4.1 Phenol oxidase ($\mu \text{ mol hr}^{-1} \text{ g}^{-1}$) in bulk soil, macro and micro-aggregate as affected by 11- years of conservation agriculture under a maize-mustard system in an Inceptisol

Considering the phenol oxidase activity within the macro- and micro- aggregates, it was found that T₅ treatment recorded highest phenol oxidase activity within both micro- and macro-aggregates at 0-5 cm depth. Whereas at 5-15 cm depth, T₄ and T₂ treatments were found to record highest phenol oxidase activity within macro- and micro-aggregates, respectively, which were also at par with T₅ treatment. Conventional tillage systems (T₆ and T₇) always recorded lowest phenol oxidase activity within macro- and micro-aggregates. Phenol oxidase activity within macro- and micro- aggregates was always higher under sub surface than the top soil (0-5 cm) layer.

4.2.1. Distribution of coarse particulate organic matter (cPOM_M), micro-aggregates inside macro-aggregates (mM) and silt and clay (s+c_M) present within macro-aggregates

Table 4.11. Percentage distribution of coarse particulate organic matter (cPOM_M), micro-aggregates inside macro-aggregates (mM) and silt and clay (s+c_M) present within macro-aggregates as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol

Treatment	cPOM_M (g 100 g ⁻¹ of bulk soil)	mM(g 100 g ⁻¹ of bulk soil)	s+c_M(g 100 g ⁻¹ of bulk soil)
T ₁ : ZTMz(-R)–ZTM(-R)	4.79 ^{cd}	38.8 ^d	8.84 ^{de}
T ₂ : ZTMz+R–ZTM+R	5.29 ^{bc}	39.8 ^{cd}	9.31 ^{cd}
T ₃ : ZTMz+R+BM–ZTM+R	5.44 ^b	41.4 ^b	8.84 ^{de}
T ₄ : ZTMz(-R)–ZTM(-R)– ZTMB(-R)	5.32 ^b	40.9 ^{bc}	10.4 ^{bc}
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	6.12 ^a	45.3 ^a	8.12 ^e
T ₆ : CTMz(-R)–ZTM(-R)	4.33 ^d	35.3 ^e	10.5 ^b
T ₇ : CTMz–CTM	3.59 ^e	33.2 ^f	12.2 ^a
LSD (<0.05)	0.53	1.55	1.17

For each column, different letters indicate that the treatment means are significantly different at $P < 0.05$ according to Tukey's HSD Test for separation of means

The coarse particulate organic matter (cPOM_M), micro-aggregates within macro-aggregates (mM) and silt and clay in macro-aggregates (s+c_M) were significantly affected by different tillage practices along with residue retention (Table 4.11). Highest amount of cPOM_M and mM fraction was found in the T₅ (ZTMz+R–ZTM+R–ZTMB+R) plots and lowest was in the T₇ (CTMz–CTM) treatment. All the ZT plots with and without residue retention had significantly higher cPOM_M than the conventional tillage i.e. T₇ (3.59 g 100 g⁻¹ of bulk soil) plot. Contradictorily, s+c_M was highest (12.22 g 100 g⁻¹ of bulk soil) under T₇, while T₅ recorded the lowest s+c_M (8.12 g 100 g⁻¹ of bulk soil), denoting increased silt + clay fraction in macroaggregates under conventional tillage.

4.2.2. Distribution of light fraction (LF_mM), intra-aggregate particulate organic matter (iPOM_mM) and silt and clay (s+c_mM) inside micro-aggregates within macro-aggregate

Table 4.12. Percentage distribution of light fraction (LF_mM), intra-aggregate particulate organic matter (iPOM_mM) and silt and clay (s+c_mM) inside micro-aggregates within macro-aggregate as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol

Treatment	LF_mM (g 100 g ⁻¹ of bulk soil)	iPOM_mM (g 100 g ⁻¹ of bulk soil)	s+c_mM (g 100 g ⁻¹ of bulk soil)
T ₁ : ZTMz(-R)–ZTM(-R)	5.95 ^b	21.1 ^d	11.8 ^b
T ₂ : ZTMz+R–ZTM+R	8.64 ^a	23.3 ^c	7.78 ^d
T ₃ : ZTMz+R+BM–ZTM+R	4.21 ^{bc}	24.1 ^c	13.2 ^a
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	5.98 ^b	26.9 ^b	8.06 ^{cd}
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	2.60 ^c	33.6 ^a	9.07 ^c
T ₆ : CTMz(-R)–ZTM(-R)	5.82 ^b	18.8 ^c	10.7 ^b
T ₇ : CTMz–CTM	5.38 ^b	16.4 ^f	11.4 ^b
LSD (<0.05)	1.89	2.05	1.28

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

Different fractions inside micro-aggregates within macro-aggregates showed significantly varied results with different tillage and residue management practices (Table 4.12). The light fraction (LF_mM) inside micro-aggregates within macro-aggregate was

highest under T₂ (ZTMz+R–ZTM+R) treatment and the lowest was recorded with T₅ treatment. While, the iPOM_mM fraction was recorded highest and lowest fraction under T₅ and T₇ (CTMz–CTM) treatments, respectively, and s+c_mM was observed highest and lowest under T₃ (ZTMz+R+BM–ZTM+R) and T₂ treatments, respectively.

4.2.3. Distribution of light fraction (m_LF), intra-aggregate POM (iPOM_m) and silt and clay (s+c_m) within free microaggregates

The distributions of light fraction (m_LF), intra-aggregate POM (iPOM_m) and silt and clay (s+c_m) within free microaggregates are given in Table 4.13. m_LF fraction was highest (8.00 g 100 g⁻¹ of bulk soil) under T₅ which was 99.5 % higher than T₇ treatment. However, T₇ treatment recorded highest iPOM_m (25.34 g 100 g⁻¹ of bulk soil) and s+c_m (9.55 g 100 g⁻¹ of bulk soil) fractions which were at par with T₁ (ZTMz(-R)–ZTM(-R)) and T₂ treatments. The lowest values for iPOM_m and s+c_m was recorded with T₄ (ZTMz(-R)–ZTM(-R)–ZTMB(-R)) and T₅ treatments, respectively.

Table 4.13. Percentage distribution of light fraction (m_LF), intra-aggregate POM (iPOM_m) and silt and clay (s+c_m) within free micro-aggregates as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol in the 0-5 cm soil layer

Treatment	LF_m (g 100 g ⁻¹ of bulk soil)	iPOM_m (g 100 g ⁻¹ of bulk soil)	s+c_m (g 100 g ⁻¹ of bulk soil)
T ₁ : ZTMz(-R)–ZTM(-R)	4.84 ^c	24.8 ^{ab}	8.55 ^b
T ₂ : ZTMz+R–ZTM+R	5.58 ^b	24.2 ^{bc}	9.38 ^a
T ₃ : ZTMz+R+BM–ZTM+R	5.78 ^b	20.9 ^d	5.98 ^e
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	4.73 ^c	19.7 ^c	6.56 ^d
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	8.00 ^a	21.5 ^d	7.46 ^c
T ₆ : CTMz(-R)–ZTM(-R)	3.80 ^d	23.5 ^c	7.55 ^c
T ₇ : CTMz–CTM	4.01 ^d	25.3 ^a	9.55 ^a
LSD (<0.05)	0.43	0.88	0.30

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.2.4 Total C distribution in cPOM_M, mM, s+c_M, mM_LF, iPOM_mM, s+c_mM, m_LF, iPOM_m and s+c_m fractions

The total carbon (TC, g kg⁻¹) in free coarse particulate organic matter between macro-aggregates (cPOM_M), micro-aggregates within macro-aggregates (mM) and silt and clay in macro-aggregates (s+c_M) were significantly affected by conservation agriculture practices (Table 4.14). T₅ treatment had significantly highest TC in cPOM_M (10.19 g kg⁻¹), mM (12.12 g kg⁻¹) and s+c_M (1.86 g kg⁻¹) fractions which were 76.30, 66.48 and 81.35 % higher than the conventional tillage i.e. T₇, respectively. All the CA management treatment also had significantly higher TC (g kg⁻¹) content in free coarse particulate organic matter between macro-aggregates (cPOM_M), micro-aggregates within macro-aggregates (mM) and silt and clay in macro-aggregates (s+c_M) than T₆ and T₇ treatments.

Table 4.14. Total carbon (TC, g kg⁻¹) in coarse particulate organic matter (cPOM_M), micro-aggregates inside macro-aggregates (mM) and silt and clay (s+c_M) present within macro-aggregates as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol in the 0-5 cm soil layer

Treatment	cPOM_M_M TC (g kg ⁻¹)	Mm TC (g kg ⁻¹)	s+c_M TC (g kg ⁻¹)
T ₁ : ZTMz(-R)–ZTM(-R)	8.18 ^e	8.73 ^c	8.27 ^d
T ₂ : ZTMz+R–ZTM+R	8.64 ^d	8.92 ^c	8.79 ^c
T ₃ : ZTMz+R+BM–ZTM+R	9.67 ^c	7.68 ^d	9.86 ^b
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	9.79 ^b	9.75 ^b	9.97 ^b
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	10.2 ^a	12.1 ^a	11.9 ^a
T ₆ : CTMz(-R)–ZTM(-R)	5.96 ^f	7.75 ^d	6.72 ^e
T ₇ : CTMz–CTM	5.78 ^g	7.28 ^d	6.54 ^f
LSD (<0.05)	0.11	0.64	0.16

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

Data pertaining to the total carbon (TC, g kg⁻¹) in light fraction (LF_mM), intra-aggregate particulate matter (iPOM_mM) and silt and clay (s+c_mM) inside micro-aggregates within macro-aggregate were presented in the Table 4.15. The total carbon was significantly affected by different conservation agriculture management practices. In T₅ treatment, the highest TC values were reported in LF_mM (13.16 g kg⁻¹), iPOM_mM (6.12 g

kg⁻¹) and s+c_mM (7.26 g kg⁻¹) fractions, which were significantly higher than T₆ (CTMz(-R)–ZTM(-R)) and T₇ (CTMz-CTM) treatments.

Table 4.15. Total carbon (TC, g kg⁻¹) in light fraction (LF_mM), intra-aggregate particulate matter (iPOM_mM) and silt and clay (s+c_mM) inside micro-aggregates within macro-aggregate as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol in the 0-5 cm soil layer

Treatment	LF_mM TC (g kg ⁻¹)	iPOM_mM TC (g kg ⁻¹)	s+c_mM TC (g kg ⁻¹)
T ₁ : ZTMz(-R)–ZTM(-R)	8.50 ^c	3.96 ^e	4.12 ^d
T ₂ : ZTMz+R–ZTM+R	8.98 ^c	4.54 ^d	4.78 ^c
T ₃ : ZTMz+R+BM–ZTM+R	8.97 ^c	4.99 ^c	5.13 ^b
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	11.2 ^b	5.20 ^b	7.21 ^a
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	13.2 ^a	6.12 ^a	7.26 ^a
T ₆ : CTMz(-R)–ZTM(-R)	8.05 ^c	2.65 ^g	4.09 ^d
T ₇ : CTMz–CTM	8.25 ^c	2.96 ^f	5.17 ^b
LSD (<0.05)	1.47	0.14	0.14

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

Total carbon (TC, g kg⁻¹) in light fraction (LF_m), intra-aggregate particulate matter (iPOM_m) and silt and clay (s+c_m) inside micro-aggregates within macro-aggregate were presented in the Table 4.16. The total carbon in different fractions was significantly affected by different conservation agriculture management practices. The total carbon under these fractions were higher under T₅ which were 11.89, 6.37 and 7.32 g kg⁻¹ for LF_m, iPOM_m and s+c_m respectively. The conventional tillage practices had lesser TC in these fractions than CA plots. The highest values were 54.41, 121.95 and 86.73 % higher over T₆ treatment in their respective fractions. The total carbon content in light fraction (LF_m), intra-aggregate particulate matter (iPOM_m) and silt and clay (s+c_m) inside micro-aggregates within macro-aggregate fractions under T₅ treatment were also 49.93, 87.35 and 56.74 % higher than T₇ treatment, respectively.

Table 4.16. Total carbon (TC, g kg⁻¹) in light fraction (LF_m), intra-aggregate POM (iPOM_m) and silt and clay (s+c_m) within free micro-aggregates as affected by 11-years of

Treatment	Bulk soil TC stock(Mg ha ⁻¹)	Macro-aggregates TC stock	Micro-aggregates TC stock(Mg ha ⁻¹)	Silt+clay TC stock(Mg ha ⁻¹)
conservation agriculture under a maize-mustard system in an Inceptisol in the 0-5 cm soil layer				
Treatment	LF_m TC (g kg ⁻¹)	iPOM_m TC (g kg ⁻¹)	s+c_m TC (g kg ⁻¹)	
T ₁ : ZTMz(-R)–ZTM(-R)	7.68 ^e	3.53 ^e	4.05 ^e	
T ₂ : ZTMz+R–ZTM+R	7.89 ^d	4.68 ^d	4.52 ^d	
T ₃ : ZTMz+R+BM–ZTM+R	8.57 ^c	5.26 ^c	4.98 ^c	
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	11.0 ^b	5.46 ^b	7.10 ^b	
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	11.9 ^a	6.37 ^a	7.32 ^a	
T ₆ : CTMz(-R)–ZTM(-R)	7.70 ^e	2.87 ^f	3.92 ^e	
T ₇ : CTMz–CTM	7.93 ^d	3.40 ^e	4.67 ^d	
LSD (<0.05)	0.13	0.14	0.17	

For each column, different letters indicate that the treatment means are significantly different at $P < 0.05$ according to Tukey's HSD Test for separation of means

4.2.5 Total carbon (TC) stock (Mg ha⁻¹) content in bulk soils and soil aggregates

Table 4.17 contains the results of total carbon (TC) stock (Mg ha⁻¹). After 11-years of CA practices, the ZT plots had significantly higher TC content than CT, irrespective of crop residue addition in the topsoil (0-5 cm) (Table 1). The T₅ treatment resulted highest TC stock (7.39 Mg ha⁻¹) in bulk soil. This was 16.64 % higher than T₇ treatment at surface soil layer. The lowest carbon stock was found in T₇ (6.35 Mg ha⁻¹). The TC stock within macro and micro-aggregates were 60.81 and 55.72 % higher in the T₅ treatment compared with T₇, respectively (table 4.20). The silt + clay associated-C content was not improved by ZT. In general, it was observed that higher TC stock content was associated with macro-aggregates followed by micro-aggregates and silt + clay.

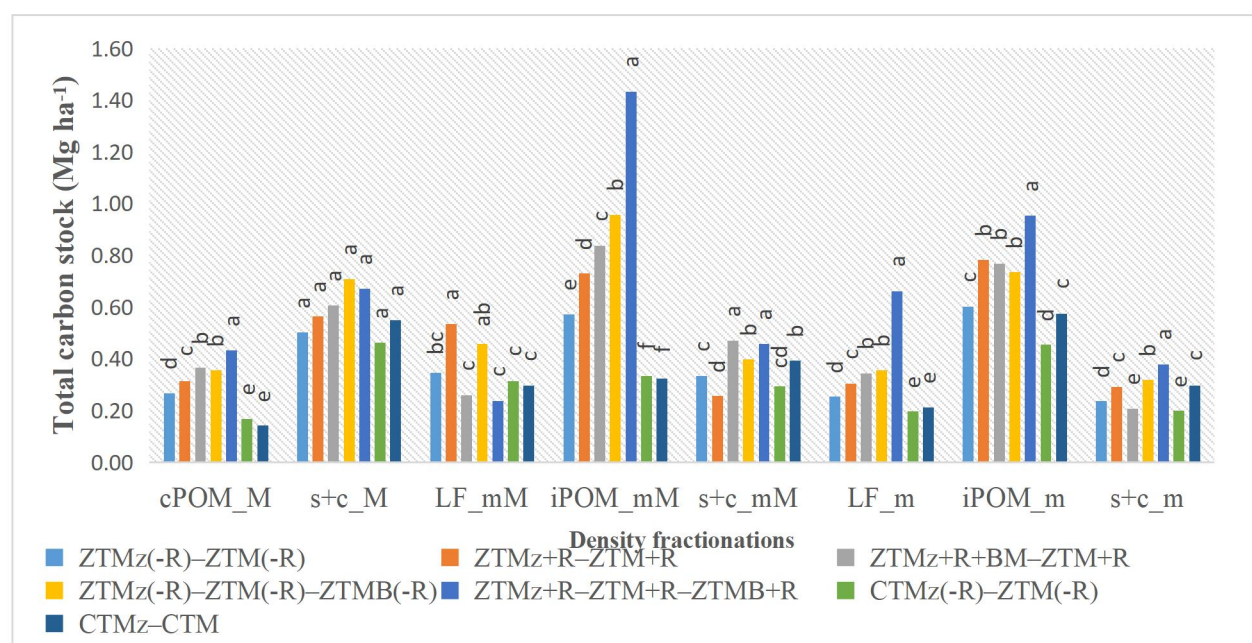
Table 4.17. Total carbon (TC, Mg ha⁻¹) stock in bulk soil, macro-aggregates, micro-aggregates and silt + clay as influenced by 11-years of tillage and residue management under a maize-mustard system in an Inceptisol

(Mg ha⁻¹)

T ₁ : ZTMz(-R)–ZTM(-R)	6.64 ^{bcd}	3.76 ^c	2.49 ^b	0.54 ^d
T ₂ : ZTMz+R–ZTM+R	6.74 ^{bcd}	3.87 ^c	2.50 ^b	0.38 ^e
T ₃ : ZTMz+R+BM–ZTM+R	6.81 ^{bc}	4.43 ^b	2.29 ^c	0.69 ^{bc}
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	6.95 ^b	4.57 ^b	2.26 ^c	0.76 ^{ab}
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	7.39 ^a	5.13 ^a	2.99 ^a	0.22 ^f
T ₆ : CTMz(-R)–ZTM(-R)	6.48 ^{cd}	3.43 ^d	2.07 ^d	0.84 ^a
T ₇ : CTMz–CTM	6.35 ^d	3.19 ^e	1.92 ^e	0.66 ^c
LSD (<0.05)	0.43	0.16	0.11	0.11

For each column, different letters indicate that the treatment means are significantly different at $P < 0.05$ according to Tukey's HSD Test for separation of means

4.2.6. Total carbon (TC) stock content within cPOM_M, s + c_M, LF_mM, iPOM_mM, s+c_mM, LF_m, iPOM_m and s + c_m fractions of the surface soil



Bars with similar lowercase letters are not significantly different at $p < 0.05$ according to Tukey's HSD test

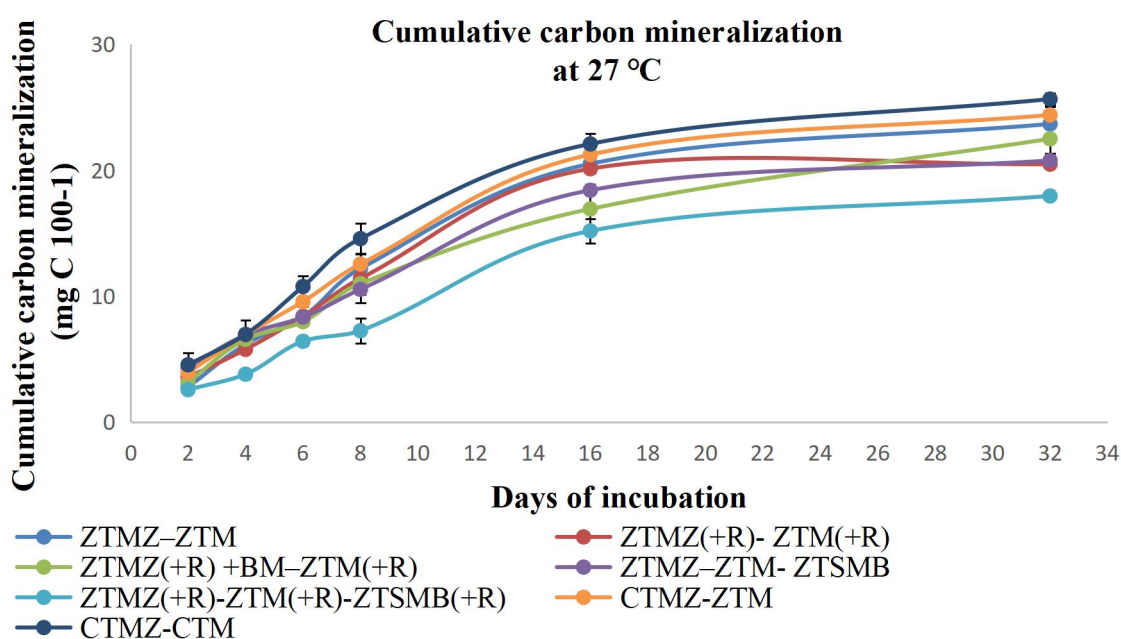
Figure 4.2: Total carbon (TC) stock (Mg ha⁻¹) in cPOM_M, s + c_M, LF_mM, iPOM_mM, s + c_mM, LF_m, iPOM_m and s + c_m fractions as affected by 11-years of conservation agriculture in an Inceptisol in the 0-5 cm soil layer

The total carbon stock in different fractions under conservation agriculture is given in Fig 4.2. Different tillage and residue retention treatments had significant influence on total carbon stock in different fractions. Different fractions of total carbon stock shows that T₅ treatment recorded higher TC stock in all the fractions except LF_mM, where T₂ had the highest total carbon stock (0.54 Mg ha⁻¹), while the lowest (0.24 Mg ha⁻¹) was under T₅. In other fractions, the lowest carbon stock was recorded under conventional tillage plots (T₆ and T₇).

4.3. Cumulative carbon mineralization (mg C 100 g⁻¹) and temperature sensitivity (Q₁₀) of SOC as affected by conservation agriculture management practices under maize-mustard system in an Inceptisol

4.3.1. Cumulative mineralization (Ct) of bulk soil

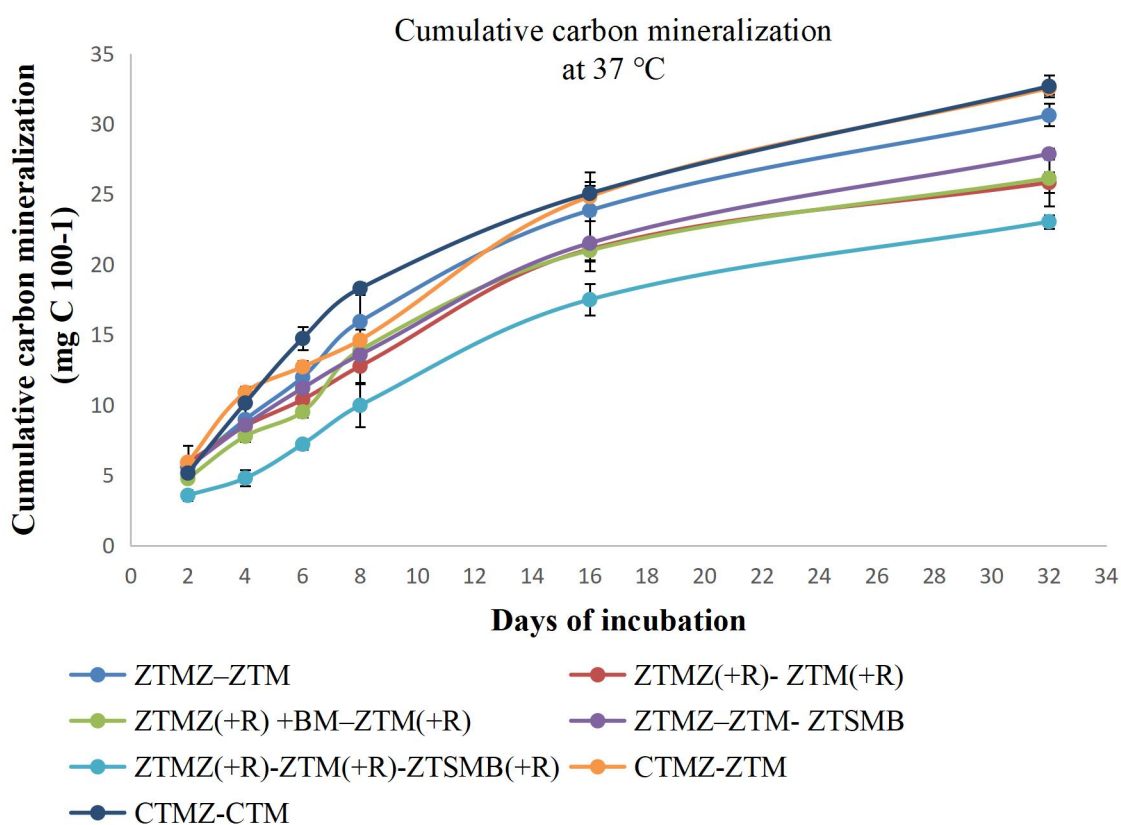
At 27°C, highest cumulative carbon mineralization (Ct) was found in T₇ (CTMz-CTM) i.e., Day 2, 4, 6, 8 16 and 32 (Figure 4.1). On Day 2 and 4, there was no significant difference among treatments. On Day 6, T₇ treatment had 66.7 % higher Ct (10.7 mg C 100 g⁻¹) than T₅ (ZTMz+R–ZTM+R–ZTMB+R), which was at par with T₆ (CTMz(-R)–ZTM(-R)) treatment. Similarly, on Day 8, T₇ had 31.5 %, 39.04 % and 101.37 % higher Ct than T₂, T₄ and T₅, respectively, in the 0-5 cm soil depth at 27 °C. Similarly on 16th and 32nd day, the highest Ct (22.1 and 25.6 mg C 100 g⁻¹) was recorded in T₇ (Table 4.21.)



P < 0.05: Day2: NS Day4: NS Day6: 3.61
 Day8: 5.74 Day16: 6.81 Day32: 3.46

Fig 4.3 Effect of 11-years of conservation agriculture under a maize-mustard system on cumulative carbon mineralization (Ct) at 27 °C in bulk soil from 0- 5 cm depth in an Inceptisol

At higher temperature (37°C), cumulative carbon mineralization in bulk soil (0-5 cm) was higher in all the treatments than that at 27°C, irrespective of treatments (Figure 4.2). At 37°C, highest cumulative carbon mineralization (Ct) was found in T₇ i.e., Day 2, 4, 6, 8 16 and 32 (Figure 4.2). On Day 2, 4 and 16 there was no significant difference among treatments. On Day 6, T₇ treatment had 104.1 % higher Ct (7.20 mg C 100 g⁻¹) than T₅, which was at par with T₆ treatment. Similarly, on Day 8, T₇ had 42.9 %, and 83.5 % higher Ct than T₂ and T₅, respectively, in the 0-5 cm soil depth at 37 °C. Similarly on 32nd day, the highest Ct (32.7 mg C 100 g⁻¹) was recorded in T₇. The T₆ treatment had similar Ct to T₇ treatment on 32nd Day (Table 4.21).



P < 0.05: Day2: NS Day4: NS Day6: 4.59
 Day8: 6.66 Day16: NS Day32: 4.35

Fig 4.4 Effect of 11-years of conservation agriculture under a maize-mustard system on cumulative carbon mineralization (Ct) at 37 °C in bulk soil from 0- 5 cm depth in an Inceptisol

4.3.2 Decay rate (Kc) of soil organic carbon mineralization

The decay rates (Kc) of SOC in bulk soils significantly varied according to tillage and residue management under conservation agriculture practices. At 27 °C, T₇ treatment had highest Kc value which was 94.5 % higher than Kc of T₅ treatment (Table 4.18). While at higher temperature (37 °C), decay rate was higher than 27 °C temperature. CTMz–CTM had highest decay rate at 37 °C, which was 110 and 134 % higher than T₄ and T₅ treatments, respectively. The T₆ treatment had similar Kc to T₇ treatment at 27 and 37 °C temperatures. The conventional tillage plots always had higher values of Kc compared with the zero tillage plots.

Table 4.18 Cumulative carbon mineralization (mg C 100 g⁻¹) as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol in the 0-5 cm soil layer

Treatment	Cumulative carbon mineralization (mg C 100 g ⁻¹)	
	27 ° C	37 ° C
T ₁ : ZTMz(-R)–ZTM(-R)	23.7 ^{ab}	30.6 ^{ab}
T ₂ : ZTMz+R–ZTM+R	20.5 ^{bc}	25.8 ^{cd}
T ₃ : ZTMz+R+BM–ZTM+R	22.5 ^{ab}	26.1 ^{cd}
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	20.8 ^{bc}	27.9 ^{bc}
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	18.0 ^c	23.0 ^d
T ₆ : CTMz(-R)–ZTM(-R)	24.4 ^a	32.5 ^a
T ₇ : CTMz–CTM	25.6 ^a	32.7 ^a
LSD (<0.05)	3.46	4.35

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.3.3 Temperature sensitivity of SOC decomposition (Q₁₀)

The temperature sensitivity (Q₁₀) values which denote the increase of reaction rate for raising 10°C temperature can also be used as an alternative measure of temperature sensitivity. These Q₁₀ values of soil C mineralization were significantly affected by tillage and residue management in bulk soils (Table 4.19). Highest temperature sensitivity (Q₁₀-1.495) was observed in case of T₇ among all other tillage and residue treatments, which was 1.28 and 1.39 times more than T₃ and T₅, respectively.

Table 4.19. Rate of carbon mineralization (K_c) and temperature sensitivity (Q₁₀) as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol in the 0-5 cm soil layer

Treatment	Rate of carbon mineralization (K _c *10 ⁻³) day ⁻¹		Q ₁₀
	27 °C	37 °C	
T ₁ : ZTMz(-R)–ZTM(-R)	1.11 ^b	1.38 ^b	1.25 ^d
T ₂ : ZTMz+R–ZTM+R	1.05 ^b	1.40 ^b	1.33 ^c
T ₃ : ZTMz+R+BM–ZTM+R	1.13 ^b	1.31 ^b	1.17 ^e
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	0.85 ^c	1.01 ^c	1.25 ^d
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	0.73 ^c	0.91 ^c	1.07 ^f
T ₆ : CTMz(-R)–ZTM(-R)	1.42 ^a	2.03 ^a	1.43 ^b
T ₇ : CTMz–CTM	1.42 ^a	2.13 ^a	1.50 ^a
LSD (<0.05)	0.13	0.18	0.050

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.3.4 Total SOC mineralization (mg C 100 g⁻¹)

The mineralization of SOC in bulk soils significantly varied according to tillage and residue management under conservation agriculture practices. At 27 °C, T₇ treatment had highest (3.29 mg C 100 g⁻¹) mineralization of SOC which was 66.16 % higher than T₅ treatment (Table 4.20). Irrespective of the treatments, at temperature 37 °C, the SOC mineralization was higher than treatments at 27 °C temperature. Similarly at 37 °C, the plots had highest SOC mineralization, which was 41.8 and 64.1 % higher than T₃ and T₅ treatments, respectively. The T₆ treatment had similar total SOC mineralization to T₇ treatment both at 27 and 37 °C temperatures. The conventional tillage plots always had higher values of SOC mineralization compared with the zero tillage plots, irrespective of the temperatures.

Table 4.20 Proportion of total SOC mineralized (mg C 100 g⁻¹) from bulk soil after 32 days as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol in the 0-5 cm soil layer

Treatment	% Total SOC mineralization (mg C 100 g ⁻¹)	
	27 ° C	37 ° C
T ₁ : ZTMz(-R)–ZTM(-R)	2.80 ^{bc}	3.62 ^b
T ₂ : ZTMz+R–ZTM+R	2.39 ^{cd}	3.01 ^{cd}
T ₃ : ZTMz+R+BM–ZTM+R	2.53 ^{cd}	2.94 ^{cd}
T ₄ : ZTMz(-R)–ZTM(-R)–ZTMB(-R)	2.36 ^{de}	3.17 ^{bc}
T ₅ : ZTMz+R–ZTM+R–ZTMB+R	1.98 ^e	2.54 ^d
T ₆ : CTMz(-R)–ZTM(-R)	3.09 ^{ab}	4.14 ^a
T ₇ : CTMz–CTM	3.29 ^a	4.17 ^a
LSD (<0.05)	0.41	0.49

For each column, different letters indicate that the treatment means are significantly different at P<0.05 according to Tukey's HSD Test for separation of means

4.4 Correlation of labile and recalcitrant carbon pools with MWD, glomalin, SMBC and C cycling enzymes

Table 4.21: Correlation of labile and recalcitrant carbon pools with MWD, glomalin, SMBC and C cycling enzymes at soil depth 0-5 cm

From the correlation studies it revealed that labile carbon pool was positively and significantly correlated ($p < 0.01$) with SMBC, DHA and β -glucosidase, and negatively

5-15 cm	Labile carbon	Recalcitrant carbon	MWD	Glomalin	DHA	β -glucosidase	Phenol oxidase	MBC
Labile carbon	1							
Recalcitrant carbon	-0.791*	1						
MWD	0.971**	-0.842*	1					
Glomalin	0.73	-0.558	0.797*	1				
DHA	0.639	-0.719	0.715	0.800*	1			
β -glucosidase	0.774*	-0.811*	0.820*	.849*	0.728	1		
Phenol oxidase	-0.639	0.848*	-0.735	-0.613	-0.517	-0.867*	1	
MBC	0.931**	-.793*	0.896**	0.794*	0.809*	0.839*	-0.593	1
** Correlation is significant at the 0.01 level (2-tailed).								
* Correlation is significant at the 0.05 level (2-tailed).								

correlated with recalcitrant carbon and phenol oxidase activity in surface (0-5 cm) and subsurface (5-15 cm) soil layers (Table 4.21). The glomalin content was correlated significantly with the stability of soil aggregates (as indicated by the MWD) and SMBC at both depths. The recalcitrant carbon was positively and significantly ($p < 0.01$) correlated with phenol oxidase activity at 5-15 cm soil depth only (Table 4.22).

Table 4.22: Correlation of labile and recalcitrant carbon pools with MWD, glomalin, SMBC and C cycling enzymes at soil depth 5-15 cm

0-5 CM	Labile carbon	Recalcitrant carbon	MWD	Glomalin	DHA	β -glucosidase	Phenol oxidase	MBC
Labile carbon	1							
Recalcitrant carbon	-0.51	1						
MWD	0.932**	-0.22	1					
Glomalin	0.865*	-0.26	0.904**	1				
DHA	0.898**	-0.169	0.980**	0.861*	1			
β -glucosidase	0.920**	-0.166	0.965**	0.930**	0.923**	1		
Phenol oxidase	-0.158	0.737	0.191	0.113	0.227	0.115	1	
MBC	0.882**	-0.094	0.944**	0.927**	0.902**	0.987**	0.205	1
** Correlation is significant at the 0.01 level (2-tailed).								
* Correlation is significant at the 0.05 level (2-tailed).								

5. DISCUSSION

The present study was carried out in an ongoing conservation agriculture experiment initiated in 2010-11 at the Research Farm of Indian Council of Agricultural Research - Indian Agricultural Research Institute (ICAR-IARI), New Delhi. The effect of 11-years of tillage and crop residue management on soil C pools, its stock, stabilization of soil organic C within aggregates and temperature sensitivity soil organic carbon were studied extensively. The results obtained are discussed in this chapter, under the following headings:

5.1. Bulk density

Bulk density (BD) increases with soil depth due to a decrease in SOC content, an increase in compactive forces, and the absence of mechanical soil inversion (Bhattacharyya *et al.*, 2012). Higher BD under ZT compared to CT (Table 4.2) may be attributable to the closer packing of soil materials under ZT compared to CT. This is due to the fact that tillage reduces the size of aggregates and, consequently, decreases the quantity of soil solid per unit volume (Hill and Cruse, 1985). The loosening of soil by tillage equipment and the incorporation of crop residues into the plough-layer also contributed to significantly lower BD under CT in the surface soil layers (Hussain *et al.*, 1998; Rani *et al.*, 2017).

5.2. Soil carbon

In the present study, total carbon (TC) and total organic carbon (TOC) varied significantly ($p < 0.05$) across the soil layers (Table 4.3), and CA-based practices dominated over the CT-based practices, reinforcing previous findings that adoption of CA-based production systems would increase the total carbon and its different fractions (Parihar *et al.*, 2018, Mondal *et al.*, 2019). The CA-based ZT along with the surface crop residue (maize, mustard and mungbean) retention delays the decaying process that usually results in less soil disturbance (Alam *et al.*, 2014), reduced oxidation of the soil organic matter (Parihar *et al.*, 2018) with more root exudates/root biomass (Sahoo *et al.*, 2019), thereby, physical protection of particulate organic material. It also leads to the greater accumulation of organic matter in upper soil layers (Machado and Silva, 2001, Luo *et al.*, 2010). Similarly, lower TC in the CT-based treatment is mainly associated to the intensive soil tilling (Rhoton, 2000); that exposes organic matter and increases its susceptibility to the microbial attack (Six *et al.*, 2000).

In the present study, soil inorganic carbon (SIC) was not affected by conservation tillage management practises in both depths (0-5 and 5-15 cm, respectively) due to mechanism to

accumulation of SIC in the soil. The SIC is generally pedogenic carbonates and is not influenced by increase in crop residue derived C. Changes in environmental conditions like soil acidification because of addition of N fertilization, N fixation by legumes or intensification of rewetting cycles due to irrigation could release great amounts of SIC and increase CO₂ emission. Moreover, many authors reported that most of the SIC content are located in depth more than one meter due to partial eluviation and redistribution of carbonates (Díaz-Hernández *et al.*, 2003; Wang *et al.*, 2010).

5.3. Soil aggregation and aggregate associated carbon

Larger macro-aggregates reduced with increased tillage intensity, and this was most significant at 0–5 cm depth. This may have altered soil aggregate stability reflected by lesser MWD, which was higher under ZT treatments (Table 4.6), irrespective of crop residue management (Zhang-liu *et al.* 2013; Chellappa *et al.* 2021; Liu *et al.*, 2021). Even distribution of external organic input in the soil profile caused by tillage could explain lesser abundance of water-stable aggregate in the CT compared with ZT across the tillage depth. The increase of macro-aggregates in ZT, particularly in the 0–5 cm layer, could be attributed to decreased mechanical disturbance, permanent return and retention of organic soil cover, and larger biological activity under this system. Greater population of termites, beetles, and millipedes may influence soil aggregation in arid environments where other ecosystem engineers (earthworms) are limited (Sithole *et al.*, 2018).

Surface retention of crop residues affects soil aggregation in many ways, as follows: 1) it protects soil aggregates from raindrop impact (Blanco-Canqui and Lal, 2009). 2) Intermediary metabolic products generated during microbial decomposition act as binding agents during macroaggregate formation and enhance aggregate stability (Somasundaram *et al.*, 2017). 3) Continuous crop residue addition promotes substrate availability and water retention, boosting microbial activity (Balota *et al.*, 2004; Denef and Six, 2005). 4) Crop residue retention boosts earthworm activity, promoting good soil structure (Nyamadzawo *et al.*, 2009).

The increments in C due to adoption of CA were more prominent in case of macro-aggregate associated C, compared with micro-aggregate associated C (Table 4.7). These results revealed that the macro-aggregates were the chief contributor towards the CA-mediated increment in soil C. Higher concentration of macro-aggregate associated C under CA compared with CT may be attributed to the following reasons: 1) slower turnover rates of

macro-aggregates, 2) physical protection of soils by mulching with crop residue combined with ZT. Under CA, fresh organic matter (e.g., fine roots, fungal hyphae, polysaccharides) inputs act as a cementing agent, and bind together the soil micro-aggregates or peripheral elementary particles to form macro-aggregates, in turn, physically protecting OC from decomposition by soil microorganisms (Tripathi *et al.*, 2014; Mustafa *et al.*, 2020). The enhanced aggregation under CA ultimately resulted in greater SOC stabilization (Yu *et al.*, 2022). In the process, formation of micro-aggregates within macro-aggregates takes place, which are considered to be one of the most stable soil C reservoirs (Balesdent *et al.*, 2000).

Irrespective of crop residue retention, the ZT recorded significantly higher total C stocks (4.17). Surface addition of crop residues, better soil aggregation (increased proportion of macro-aggregates), lower rates of macro-aggregate breakdown, slower oxidation or decomposition rates of organic matter and higher addition of root and stubble biomass over 11-years of experimentation enhanced total C (Bhattacharyya *et al.*, 2011; Zheng *et al.*, 2018; Tomar *et al.*, 2019). The crop residue retention under ZT registered further enhancements in total soil C, as compared with ZT without crop residue retention, indicating importance of crop residue management on C sequestration potential.

Previous studies (Tisdall and Oades 1982; Zhao *et al.*, 2019) have shown that straw-derived C preferentially accumulated in macroaggregates and that soil aggregate formation follows a hierarchical sequence model (*i.e.*, greater SOC with increasing aggregate size). Results from our research followed the same trend and reported higher values of macro-aggregate associated C, compared with micro-aggregates associated C. The slower turnover rates of macro-aggregates and physical protection of soils by mulching with crop residue combined with ZT might be the reasons for higher macro-aggregate-associated C content. Inherent stability of C against biochemical decomposition, limitation of O₂, sorption of SOM to soil solid, low inaccessibility for microbial degradation, control of microbial turnover by predators like nematode, protozoa and formation of micro-aggregates within macro-aggregates might also have contributed for the increased macro-aggregate-associated C (Rutherford and Juma, 1992; Balesdent *et al.*, 2000).

5.4. Lability and recalcitrance of soil organic carbon

The C lability was significantly ($p < 0.05$) higher under ZTMZ+R–ZTM+R–ZTMB+R compared with CTMz–CTM (Table 4.4). The labile C (LC) was ~60 and 51% significantly higher under ZTMZ+R–ZTM+R–ZTMB+R compared to CTMz–CTM treatment at 0-5 and

5-15 cm soil layer, respectively. The oxidation of LC pools accelerates carbon dioxide transfer from soil to atmosphere, resulting in faster turnover rates than recalcitrant C (RC). The greater accumulation of LC under ZT as compared to the CT, in both soil layers, irrespective of crop residue retention (Table 4.5) may be attributed to the fact that there was less mechanical disturbance in the ZT, which led to greater physical protection of SOC under CA. The lower LC and RC pools under CT were mainly because of lesser input of biomass C into the system because of low crop productivity and/or removing of crop residues (Kim *et al.*, 2009). The decrease in labile C in CT plots might be due to increased rate of microbial decomposition of organic matter (Seybold *et al.*, 1999) and also due to change in the structural stability of soil by disruption of aggregates (Veen and Paul, 1981). In addition, larger microbial population in topsoil of crop residue supplemented plots may have sped up the process by which C and N (added through crop residues) were mineralized, leading to greater amount of LC.

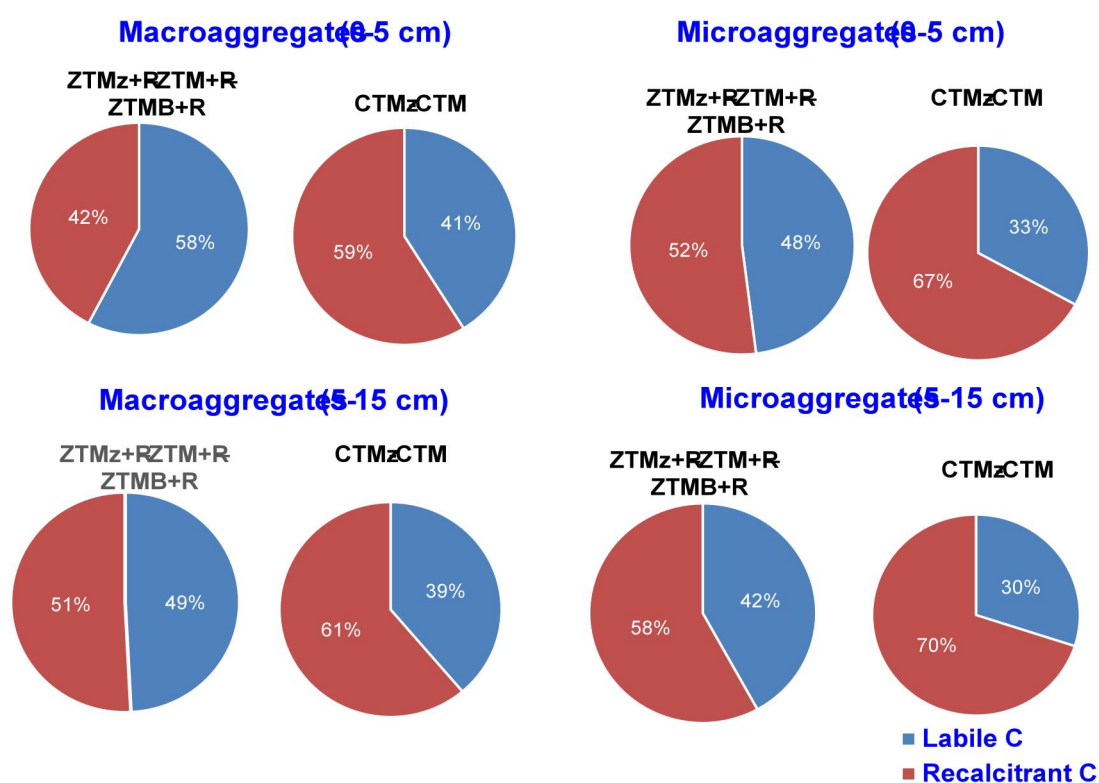


Fig 5.1 Proportion of labile and recalcitrant carbon pools in aggregates as affected by 11-years of conservation agriculture under a maize-mustard system in an Inceptisol

It has been observed that the C derived from crop residues is first incorporated into labile C pools, which then are used by microbes to make microbial products, which could be tightly bonded to the mineral soil matrix and promoted soil aggregation, generating stable carbon fraction *i.e.* RC (Angers *et al.*, 1997; Chen *et al.*, 2014; Six *et al.*, 2000). Surface retention of crop residues and non-inversion of soil generated much larger SOC build-up in topsoil compared with lower depths (Amini and Asoodar, 2015). Moderation of soil surface temperature and higher moisture retention under crop residue retention further slowed down the decomposition process (Das *et al.*, 2020). The contention was supported by several other researchers (Bhattacharyya *et al.*, 2012; Dey *et al.*, 2018; Das *et al.*, 2021). Abundance of fresh organic crop residues and greater microbial activity in 0-5 cm soil layer, promoted greater labile C, in the expense of recalcitrant C.

Irrespective of crop residue retention, conversion from CT to ZT improved both labile and recalcitrant pools of C, in soils, and inside macro- and micro-aggregates (Table 4.8) (Deng *et al.*, 2018; Zhong *et al.*, 2019). The proportion of labile carbon pools was more under ZT (R) than CT (Fig 5.1). Fresh organic matter (e.g., fine roots, fungal hyphae, polysaccharides) entered soil-bound micro-aggregates to create macro-aggregates, physically protecting OC from breakdown by soil microbes (Tripathi *et al.*, 2014; Mustafa *et al.*, 2020). The non-cellulosic polysaccharides from plants or soil microbes were the predominant components of labile carbon fraction (Liu *et al.* 2020). The increase in RC in 5-15 cm soil within micro-aggregates may be related to greater lignin and cellulose content in maize, mustard and mungbean straw residues, inadequate aeration within micro-aggregates reducing microbial breakdown rate due to decreased accessibility (Sollins *et al.*, 1996; Singh *et al.*, 2018). Formation of clay mineral complexes contributes further to the stability of soil aggregates and associated C (Jeewani *et al.*, 2021). Greater activity of nematode and protozoa in macro-aggregates under CA often keep checks on microbial turnover, in turn stabilising aggregate associated C (Rutherford and Juma, 1992).

5.5. Distributions of density fractions within macroaggregates

Irrespective of crop residue retention, the cPOM_M was greater under ZT, compared with CT (Table 4.11). Continuous addition of above-ground and below-ground plant biomass under the triple zero tillage with crop residue retention registered highest amount of cPOM_M. The cPOM_M is susceptible to microbial attack and on degradation release sticky, cement-like polysaccharide which help in the formation of microaggregates within macro-aggregates (Six *et al.*, 1999; Denef *et al.*, 2001). This led to increase in percent distribution of micro-

aggregates within macro-aggregates (mM) fraction. Averaged across the treatments, the concentration of mM was higher than cPOM_M and silt and clay fractions present within macro-aggregates (s+c_M) and this fraction might provide maximum stability to soil macro-aggregates (Modak *et al.* 2020; Trivedi *et al.*, 2021). On the contrary, continuous CT over the years broke macro-aggregates into micro-aggregates and silt plus clay, resulting in higher amounts of s+c_M, compared with ZT (Yu *et al.*, 2022).

5.6. Distributions of density fractions inside microaggregates within macroaggregates

The LF are the most labile form of C composed of partially decomposed fragments of root biomass and above ground crop residue adsorbed on mineral surface or remained within microaggregates (Boone, 1994; Modak *et al.*, 2020). The mM_LF was lowest under ZTMZ+R–ZTM+R–ZTMB+R (Table 4.12) due to the low C: N ratio of the added *mungbean* residue, causing higher loss of LF due to microbial decomposition (Dou *et al.*, 2016). On the other hand, retention of only cereal/oilseed crop residue of relatively higher C:N ratio registered higher values of mM_LF under remaining ZT treatments. On the other hand, continuous addition of organic residue fragments into different soil aggregate size fractions through sequential decomposition enhanced iPOM_mM in the ZT treatments (Huang *et al.*, 2018; Six *et al.*, 2000). This phenomenon in turn promotes plant root growth and soil microbial activity, by virtue of essential nutrients supply. As a result, greater production of aggregate-binding agents *i.e.*, microbial- and plant-polysaccharides was reported under ZT, mediating soil aggregation (Dai *et al.*, 2019). The treatment ZTMZ+R–ZTM+R–ZTMB+R had highest contents of iPOM_mM, indicating better physical protection of these fractions within microaggregates occluded by macroaggregates (Huang *et al.*, 2018). According to Six *et al.* (2000), this fraction is important in maintaining the stability of macro-aggregates due to slow turnover rate, encapsulation of iPOM by mineral matter and microbial polysaccharides and gums to form stable microaggregates containing crop residue derived C. The presence of remarkable amount of s+c_mM fraction also indicated greater role of this fraction in maintaining stability of microaggregates (Yu *et al.*, 2022).

5.7. Distributions of density fractions within free microaggregates

Similar to mM_LF, tillage management had no impact on m_LF, whereas, crop residue retention increased m_LF, irrespective of tillage (Table 4.13). The recovery efficiency of both mM_LF and m_LF were low because of adhesion of these fractions with walls of the container (Modak *et al.*, 2020; Trivedi *et al.*, 2021). The iPOM_m and s+c_m fractions are

considered as the major building blocks of micro-aggregates whether it is free or occluded inside microaggregates (Six *et al.*, 1999), which were found higher under ZT(+R) as compared with ZT.

5.8. Distribution of soil organic carbon associated with density fractions

Higher concentration of C in the cPOM_M fraction was associated with ZT than the CT treatments (Fig 4.2). According to Chatterjee and Lal (2009), crop residues when incorporated in the soil during tillage (under CT), increased mineralization of cPOM-C by soil microbes. Under ZT (+R) plots continuous addition of litter, leads to release of polysaccharides through decomposition, leading to better occlusion of carbon in cPOM (Taskin *et al.*, 2021). On the other hand, continuous tillage caused the disruption of aggregates and exposure of soil aggregate protected cPOM-C to microbial decomposition (Cambardella and Elliott, 1992; Mikha and Rice, 2004; Tiwari *et al.*, 2018) under CT. The LF was mostly influenced by the levels of C inputs (Janzen *et al.*, 1992; Six *et al.*, 1999), registering significantly higher values of mM_LF-C and m_LF-C under ZT (+R) compared with CT (Dou *et al.*, 2016). The findings suggested that despite better physical protection, SOC within micro-aggregates might be susceptible to microbial breakdown. Greater SOM decomposition resulted in significantly lower C:N ratios in LF-C, compared with that under strong mineral association under s+c_M (John *et al.*, 2005; Chivenge *et al.*, 2011). The s+c_M-associated C was less prone to loss as a result to tillage disturbance, compared with the cPOM and mM fractions (Huang *et al.*, 2010). This might be the reason for higher C content in s+c_M than LF fractions. The mM_LF were better protected leading to higher C contents compared with m_LF, (Modak *et al.*, 2020).

Irrespective of treatments, iPOM was the largest reservoir of C, among the different density fractions (Fig 4.2). The concentration of C was significantly higher in both iPOM_mM and iPOM_m fractions in the ZT treatments compared with CT treatment due to lesser rates of POM-C decomposition aided by lesser disturbances caused by tillage, raindrops *etc.* and greater abundance of microaggregates within macroaggregates. Furthermore, irrespective of the tillage treatments, the TC stock was recorded higher in the s+c_mM than the s+c_m fraction. This indicated better protection of microaggregates present inside macroaggregates rather than free microaggregates. Thus, from C sequestration point of view, protected microaggregates have slow turnover rates and are more important than that of free microaggregates.

5.9. Effect of conservation agriculture on soil microbial biomass carbon and glomalin content in bulk soil

The SMBC symbolises the ability to store and cycle nutrients (Carter, 1992) and is necessary for soil aggregate formation. Under ZTMZ+R–ZTM+R–ZTMB+R, constant and uniform supply of carbon from crop residues acted as an energy source for microorganisms, which in turn resulted in highest values of SMBC. All ZT(+R) treatments showed higher SMBC (Table 4.5) compared with CT. Abundances of microbial activity in top soil layer reflected in higher values of MBC in surface soils irrespective of treatments (Angers and Eriksen-Hamel, 2008). Crop residue retention on surface, lesser intensity of soil disturbance promoted fungal abundance and diversity (Campbell *et al.*, 1998; Hedges *et al.*, 1999; Helgason *et al.*, 2010). The fungal hyphal networks are important in recycling of C and nutrients (Johnson and Hoyt, 1999). In the present study, ZTMZ+R–ZTM+R–ZTMB+R had 68.8% more glomalin (an arbuscular mycorrhizal glycoprotein) than CTMz-CTM. Low C:N ratio of N-rich legume inputs (brown manuring), surface cover (mungbean residue), inhibited breakdown of soil glomalin under ZT(+R) plots (Singh *et al.*, 2022) (Table 4.5). Actively N₂-fixing zero-tilled mungbean might also have yielded rhizodeposits, boosting the AM fungus population, and leading to greater glomalin production. Increases in AMF hyphal length density can be accounted for greater glomalin content in treatments with legumes in the cropping system or as a surface (mungbean) application (Wang *et al.*, 2020). This may be due to the influence of host species, which regulates the hyphal development of specific AMF species (Hausmann and Hawkes, 2009) or "selects" species that penetrate roots and soil with differential vigour (Burrows, 2014). This contention is corroborated by earlier work showing a positive association between mycorrhizal colonisation, spore density, and hyphal length and soil glomalin levels (Wu *et al.*, 2014).

5.10. Effect of conservation agriculture on carbon cycling enzymes

Enzymes in soil such as dehydrogenase, β -glucosidase reflect the total range of oxidative activity and decomposition rates of soil microflora, which serves as a good indicator of microbiological activity in the soil. The CA recorded higher DHA (Table 4.9), β -glucosidase activity compared with CT, especially in upper soil layers (Table 4.10). Such higher enzyme activities under CA might be attributed to 1) higher accumulation of organic matter in soil, 2) abundance of soil microbes, 3) greater substrate availability, 4) improved soil water infiltration, 5) optimum soil moisture availability for reaction *etc* (Hobbs *et al.*, 2008; Serraj and Siddique, 2012). Positive correlation between soil organic matter and DHA (Sharma *et*

al., 2022), β -glucosidase (Almagro *et al.*, 2021) was noticed in previous studies (Dey *et al.*, 2016). Lower enzymatic activities were noticed inside aggregates compared to bulk soil as preservation of OC within the aggregates reduces the substrate availability. Abundance of fresh organic matter in macroaggregates promoted greater enzymatic activity. On the other hand, prevalence of recalcitrant SOC inside free microaggregates which fails to supply microbes with sufficient food sources, recorded significantly lower enzymatic activities (Martínez-Mena *et al.*, 2013). Phenoloxidase enzymes synthesised and deployed by soil microorganisms to counter the deleterious effects of phenolic compounds on general enzyme and microbial activity (Esiana *et al.*, 2021). The phenoloxidase activity was lower at lower depths (Fig 4.1), which may be attributed to due to decreasing oxygen availability (Pind *et al.*, 1994), which is essential for the catalysis of phenolic compounds and organic substrates in the lower depth (Esiana *et al.*, 2021). The contrasting microbial community responses are most likely the result of the complex interactions between moisture, oxygen, temperature and pH. These are sensitive to alterations in environmental conditions which affects the phenol oxidase activity in soils (Laiho, 2006). Previous studies reported that decrease in PO activity is due to increase in decomposition of organic residue (Zibilske and Bradford, 2007; Waldrop *et al.*, 2003) which is in contrast to the present study. Considering the micro and macro aggregate fractions, higher PO activity was noticed in micro in shallow depth and macro aggregate under sub-soil. High enzyme activity within microaggregates was possibly due to immobilization of extracellular enzymes, even if the C associated with microaggregates is more resistant to decomposition (Dorodnikov *et al.*, 2009).

5.11. Decay rates and temperature sensitivity of soil organic carbon mineralization

The ZT, by virtue of enhanced physical protection to SOC, promoted C accumulation (Table 4.20) and greatly inhibited C mineralization (Six *et al.*, 2002; 2004). Higher cumulative carbon mineralization (Ct) and decay rates (Kc) were found under CT compared with ZTMz+R–ZTM+R–ZTMB+R and ZTMz+R+BM–ZTM+R treatments, irrespective of thermal regimes (Table 4.19). Soil disturbances under CT directly affected C substrate availability by influencing their interaction with mineral adsorption sites and cations or indirectly by modifying external factors (e.g., temperature, moisture, aeration, pH, nutrient supply) that control SOC decomposition (Von Lützow *et al.*, 2006). Better aggregation under ZT(+R) protected SOC as intra-particulate organic matter, which resulted in significant decrease in Ct and Kc values (Balesdent *et al.*, 1990; Lamparter *et al.*, 2009).

The increase in thermal regimes augments the physiological reaction rate of organisms and microbial activity (Verma, 2010), which led to higher C mineralization *per se* at higher temperature. As evident from Figures 4.1 to 4.2, cumulative C mineralization was higher at 37 °C compared with that at 27 °C. Similar results were obtained by several other researchers (Ghosh *et al.*, 2016; Dey, 2017; Jat *et al.*, 2019; Bhattacharyya *et al.*, 2020b). The apparent temperature sensitivity of SOC mineralization depends on biophysical and biochemical factors. Higher temperature enhances dissolution and diffusion of C substrates towards active sites of enzymes. Thus, substrate availability towards microbial decomposition witnesses enhancement (Xu and Saiers, 2010; Davidson *et al.*, 2012). Desorption of otherwise recalcitrant SOM-humate complexes were also favored at elevated temperatures (Davidson and Janssens, 2006) and these factors altogether accelerated SOM decomposition leading to higher cumulative mineralization and decomposition rates at higher temperature. The ZT with lesser soil disturbance generates an *in situ* temperature insensitive process that alters the release of easily decomposable substrates and thereby reduces the decomposition rate (Von Lützow and Kögel-Knabner, 2009). There are earlier reports (Pulleman and Marinissen, 2004) depicting lower temperature sensitivity of SOC mineralization under CA-based systems when compared with conventional systems. Sandeep *et al.* (2016) reported that bed planting system had better C stability and lower temperature sensitivity of SOC mineralization at elevated temperature. Crop residue retention in ZT treatments might have promoted the C build-up mainly through physical protection, rather than developing bio-chemical recalcitrance (Six *et al.*, 2002; Jat *et al.*, 2019). This led to greater extents of SOC stabilization with lower decay rates and lesser temperature sensitivity in ZT (+R) compared with CT treatments.

5.12. Correlation of labile and recalcitrant pools with MWD, glomalin, SMBC and C cycling enzymes

The available carbon resources by crop residues activate microorganisms to produce enzymes related to the cycle of (Roldan *et al.*, 2005). Indeed, labile carbon also showed a high correlation ($p < 0.01$) with microbial activity measured by DHA and β -glucosidase activity (Table 4.21). Dehydrogenase contributes to the biological oxidation of SOM (Zhang *et al.*, 2010), and the strong correlation of labile carbon, and SMBC, with dehydrogenase activity could be explained by the effects of labile carbon as a substrate promoting growth of microbial biomass, which is associated with the dehydrogenase enzyme. With the increase in soil glomalin content, soil macro aggregation increased significantly, as evidenced by high positive values of correlation coefficient (Sekharan *et al.*, 2021) and also

due to greater microbial activity it yielded rhizodeposits, boosting the AM fungus population, and leading to greater glomalin production (Sharma *et al.*, 2022). Thus, the glomalin content was correlated significantly with the stability of soil aggregates (as indicated by the MWD) and SMBC at both the depths. Several reports (Table 4.22) on decomposition studies over few decades which have shown positive correlation between organic matter recalcitrance and oxidative enzyme activities (Herman *et al.*, 2008). $\ln(\text{BG})/\ln(\text{POX})$ activity ratio is inversely related to the relative abundance of recalcitrant carbon (Sinsabaugh and Shah, 2011).

6. SUMMARY AND CONCLUSIONS

6.1. Summary

The research work, entitled “*Soil organic carbon dynamics under conservation agriculture-based maize-mustard system in an Inceptisol*” can be summarized as follows:

The aim of this study was to understand the impacts of long-term conservation agricultural practices on carbon pools, carbon cycling enzymes, its stock and carbon stabilization within soil aggregates, carbon mineralization and its temperature sensitivity in maize - mustard system in an Inceptisol.

- The effects of tillage and residue management on soil pH and EC in the surface (0-5 cm) and subsurface (5-15 cm) depths were found to be non-significant among different treatments.
- Tillage and residue management practices had significantly affected soil bulk density at 0–5 cm, but not in 5–15 cm depth. In the 0-5 cm depth, the highest BD was recorded in ZTMz+R–ZTM+R–ZTMB+R (T₅) and ZTMz+R+BM–ZTM+R (T₃) treatments (1.39 Mg m⁻³) which was at par with different ZT, with or without residue management treatments and 3.73% higher than CTMz-CTM (T₇).
- In the 0-5 cm soil layer, triple zero tillage with residue retention had the highest total carbon (TC) (10.61 g kg⁻¹) compared to conventional tillage which recorded least TC. In 5-15 cm soil depth, TC ranged from 9.21 (T₇) to 10.26 g kg⁻¹ (T₅). Triple zero tillage with residue retention recorded the highest TC.
- Total organic carbon showed similar result as of TC, where T₅ treatment showed significantly higher TOC values of 9.29 and 8.74 (g kg⁻¹), respectively at 0-5 and 5-15 cm depths, which was 13.15 and 13.35 % higher over T₇. On contradiction, total inorganic carbon (TIC) (g kg⁻¹) showed no significant difference among the treatments in both the depth.
- T₅ was found to have increased levels of labile carbon (LC) (g kg⁻¹) at both the depths (4.51 and 3.03 g kg⁻¹) which was 59.92 and 50.74 % higher than T₇ treatment at 0-5 and 5-15 cm soil layers, respectively. While the lowest amounts of labile carbon was recorded in T₇ treatment (2.82 and 2.01 g kg⁻¹ at 0-5 and 5-15 cm, respectively)
- The recalcitrant carbon (RC) pools increased with the increase in soil depth, where the highest (5.31 g kg⁻¹) was found in ZTMz(-R)–ZTM(-R)–ZTMB(-R) (T₄), which was at par with ZTMz(-R)–ZTM(-R) (T₁), ZTMz+R–ZTM+R (T₂) and ZTMz+R+BM–

ZTM+R (T₃) treatments at 0-5 cm depth. At 5-15 cm depth, the highest (6.79 g kg⁻¹) recalcitrant carbon pool was found in CTMz(-R)–ZTM(-R) (T₆) treatment with all other treatments being at par except T₄ and T₅. The lowest recalcitrant carbon pools (4.63 and 5.67 g kg⁻¹, respectively) were recorded under T₅ treatment at 0-5 and 5-15 cm depths.

- The highest soil microbial biomass carbon (SMBC) (647.93 and 339 mg kg⁻¹ dry soil at 0-5 and 5-15 cm, respectively) was recorded in T₅, which was 171 and 150 % higher than the T₇ treatment at their respective depths. While, the lowest SMBC under 0-5 cm (238.57 mg kg⁻¹ dry soil) and 5-15 cm (135.60 mg kg⁻¹ dry soil) were noticed under T₇ and T₁ treatments, respectively.
- The significantly higher glomalin contents (11.77 and 9.85 mg g⁻¹ soil at 0-5 and 5-15 cm, respectively) were recorded in T₅, which was 67.42 and 76.8 % more than T₇ treatment at their respective depths. While, the lowest glomalin contents (7.03 and 5.07 mg g⁻¹ soil at 0-5 and 5-15 cm, respectively) were recorded in T₇ treatment.
- CA practices had a significant impact on the mean weight diameter (MWD) in both the soil layers (0–5 and 5–15 cm) after 11 years of management practices. 0-5 cm had higher MWD than 5-15 cm. T₅ treatment had significantly higher MWD i.e. 20.31 and 16.36 % more than the T₇ treatment at their respective depths.
- The macro-aggregate distribution of bulk soil was significantly affected by different tillage and residue management practices. The percentage distribution of macro-aggregates was more in the surface soil layer (0–5 cm) compared to the subsurface (5–15 cm) layer, irrespective of the treatments. The proportion of macro-aggregates was significantly higher under T₅ treatment, which was 20.36 and 17.32 % higher than the conventional tillage (T₇) at 0-5 and 5-15 cm depths, respectively.
- The distribution of micro-aggregates was significantly affected by CA management practices. At 0-5 cm depth, the highest micro-aggregate distribution was found in T₂ (39.12 %), followed by T₇ and T₁ treatments. At 5-15 cm depth, the highest micro-aggregate distribution was found in T₆ (33.60 %), followed by T₅ and T₇.
- The macro-aggregate associated carbon (g kg⁻¹) was affected significantly by different tillage and residue retention practices irrespective of the depths. T₅ treatment recorded 27.10 and 29.49 % higher macro-aggregate associated C concentration than T₇ at 0-5 and 5-15 cm depths, respectively. However, it was also noticed that macro-aggregate associated carbon decreased with increasing depth.

- TC (g kg^{-1}) in micro-aggregates (0.25-0.053 mm) at two different depths (0-5 and 5-15 cm) varied significantly among the treatments. T_5 showed significantly higher micro-aggregate associated C under both the depths (11.64 and 10.40 g kg^{-1} , respectively), which was at par with T_4 and the lowest was recorded in T_7 .
- The labile and recalcitrant pools of C were significantly affected within macro and micro-aggregates at 0-5 and 5-15 cm depth, respectively. The LC and RC pools within macro-aggregates were found higher in ZT plots than in CT plot at both the depths. The labile C pool within the micro-aggregates followed a similar trend as macro-aggregates in both topsoil and 5-15 cm. RC pool in micro-aggregates in T_5 (5.34 g kg^{-1}) and T_2 (5.75 g kg^{-1}) recorded significantly highest values at 0-5 and 5-15 cm depths, respectively.
- The dehydrogenase (DHA) and β -glucosidase activities after 11-years of CA practices were significantly affected by tillage and residue management in topsoil (0-5 cm) and in 5-15 cm soil depth. The highest DHA and β -glucosidase activity in bulk soil were found in T_5 , which were 28.65 and 89.18 %, respectively higher than T_7 treatment (lowest) at 0-5 cm depth. In general, DHA and β -glucosidase activity followed a similar trend in the 5-15 cm as that of the 0-5 cm soil layer. Within the macro- and micro- aggregates, T_5 recorded significantly highest DHA and β -glucosidase activity, irrespective of depths. Partial and complete conventional tillage systems (T_6 and T_7) always recorded lowest DHA and β -D glucosidase.
- At 0-5 cm soil layer, phenol oxidase activity was higher than the 5-15 cm under different ZT systems than CT and vice-versa at 5-15 cm depth in the bulk soil. Within the macro- and micro- aggregates, it was found that T_5 treatment recorded the highest phenol oxidase activity within both micro- and macro-aggregates at 0-5 cm depth. Whereas at 5-15 cm depth, T_4 and T_2 treatments recorded the highest phenol oxidase activity within macro- and micro-aggregates, respectively.
- To study the stabilization of organic carbon in density fractions, higher proportions of mM fraction was recorded in macro-aggregates. Similarly, iPOM_mM and iPOM_m fractions were mainly contributing in stabilization in this mM and micro-aggregate fractions, respectively. Coarse particulate organic matter (cPOM_M) and microaggregates within the macroaggregates (mM) fractions were found highest under T_5 and lowest under T_7 treatment. All the ZT plots with and without residue retention had significantly higher cPOM_M than the CT i.e. T_7 plot. Contradictorily,

s+c_M was highest (12.22 g 100 g⁻¹ of bulk soil) under T₇, while T₅ had lowest s+c_M denoting increased silt + clay fraction in macro-aggregates under CT.

- The light fraction (LF_mM) inside micro-aggregates within macro-aggregate was highest under T₂ and lowest under T₅ treatment. While, the iPOM_mM fraction recorded highest and lowest fraction under T₅ and T₇ treatments, respectively, s+c_mM was observed highest and lowest under T₃ and T₂ treatments, respectively.
- Tillage had significant impact on the light fraction (m_LF), intra-aggregate POM (iPOM_m) and silt and clay (s+c_m) within free microaggregates. m_LF fraction was highest under T₅ which was 99.5 % higher than T₇ treatment. However, T₇ treatment recorded highest iPOM_m and s+c_m fractions which were at par with T₁ and T₂ treatments. The lowest values for iPOM_m and s+c_m were recorded with T₄ and T₅ treatments, respectively.
- After 11-years of CA practices, the ZT plots had significantly higher TC stock than CT, irrespective of crop residue retention. The T₅ treatment resulted in highest TC stock, which was 16.64 % higher than T₇ treatment at 0-5 cm. The TC stock within macro and micro-aggregates in T₅ were 60.81 and 55.72 % higher over T₇, respectively. The silt + clay associated-C content was not improved by ZT. In general, higher TC stock content was associated with macro-aggregates followed by micro-aggregates and silt + clay.
- Different fractions (cPOM_M, s + c_M, LF_mM, iPOM_mM, s + c_mM, LF_m, iPOM_m and s + c_m) of total carbon stock shows that T₅ treatment recorded the highest TC stock in all the fractions except LF_mM, while T₂ and T₅ had the highest (0.54 Mg ha⁻¹) and the lowest (0.24 Mg ha⁻¹) total carbon stocks. In other fractions, the lowest carbon stock was recorded under conventional tillage plots (T₆ and T₇).
- Light fraction-C content was not only affected by zero tillage, but also due to residue retention. The C content within LF_mM and inside LF_m fraction, indicating better protection of the said protected C. The iPOM_mM and iPOM_m fractions followed by s + c_M fractions had highest total carbon stock content within macro-aggregates and micro-aggregates, respectively, in the topsoil. That indicates the role of iPOM and s + c_M fractions in SOC stabilization within the soil aggregates. Treatments with ZT with or without residue had more carbon content inside micro-aggregates within macro-aggregates (mM; combination of LF_mM, iPOM_mM and s + c_mM) than CT treatment indicating role of reduced tillage for better C stabilization than CT.

- Irrespective of treatments in incubation study, highest carbon mineralisation was recorded at higher temperature (37°C) than at 27°C. ZT treatments showed lower cumulative C mineralization (Ct) compared with CT treatments after 32 days of incubation at 27°C and 37°C. CTMz-CTM had the highest Ct (25.6 and 32.7 mg C/100g soil at 27°C and 37°C, respectively) followed by CTMz(-R)–ZTM(-R).
- CT treatments had significantly higher Kc values compared to ZT treatments with and without residue at both temperatures. However, Kc was higher at 37°C compared to that at 27°C, irrespective of treatments.

Similarly, there was a significant variation in temperature sensitivity of SOC mineralization (Q_{10}) in the 0-5 cm soil depth. CT treatment had higher Q_{10} values than ZT with and without residues showing more evolution of CO₂ with temperature fluctuation and less stabilization of SOC.

Based on the findings of the present study, it can be concluded that:

- Tillage and residue management had a significant impact on SOC pools and aggregate associated C after 11 years of CA practices. With SMBC, dehydrogenase, and β -glucosidase actives, the labile fraction of SOC exhibited positive correlation. Therefore, this shows the potential of CA practices for improving soil health and SOC buildup in the maize-mustard system.
- ZT and residue addition treatments significantly increased C within macro and microaggregates in topsoil, demonstrating their beneficial contribution towards the stabilization of SOC. Protected C was mainly seen in the iPOM_mM and iPOM_m fractions, followed by s+c_M fractions. This shows the role of iPOM and s+c_M fractions in the stabilization of SOC within soil aggregates.
- Temperature had a positive effect on SOC mineralization, with higher CO₂ evolution at higher temperatures regardless of treatment. Having higher rate of SOC mineralization, CT treatment was highly temperature sensitive (with highest Q_{10} value), indicating more CO₂ evolution and less C stabilization. In contrast, ZT with and without residue retention treatments provided better SOC protection under CA practices.
- Considering the above said points, treatment with ZTMz+R–ZTM+R–ZTMB+R (T₅) is so far the most effective treatment in carbon sequestration point of view.

Therefore, further studies would be emphasized on detailed multi-locational studies on SOC dynamics under proper nutrient management options so as to evolve soil health

centric sustainable management practices for diversified cropping system under conservation agriculture.

7. ABSTRACT

Soil organic carbon (SOC) is the third largest carbon pool after oceanic and geological pools. This pool's capacity to store C in the soil could be improved. Conservation agriculture (CA) practices that keep crop residue on the surface and use minimal tillage with diversified cropping system store more C as organic matter. The purpose of this study was to see how long-term conservation agricultural practices affected carbon pools, carbon cycling enzymes, stock and carbon stabilization within soil aggregates, carbon mineralization, and temperature sensitivity in an Inceptisol under maize-mustard system. After maize harvest, soil samples from two depth (0-5 cm and 5-15 cm) were taken from a conservation field experiment that has been going on since 2010-11 at ICAR-IARI, Pusa, New Delhi. The experiment has a randomised block design with three double-cropping zero-till systems, two triple-cropping zero-till systems with or without crop residue retention, and two conventional till systems [T₁: ZTMz(-R)-ZTM(-R); T₂: ZTMz+R-ZTM+R; T₃: ZTMz+R+BM-ZTM+R; T₄: ZTMz(-R)-ZTM(-R)-ZTMB(-R); T₅: ZTMz+R-ZTM+R-ZTMB+R; T₆: CTMz(-R)-ZTM(-R); T₇: CTMz-CTM]. The highest total carbon (TC) was recorded in the T₅ treatment, which was on par with T₄ and 11.68% higher than the T₇ treatment at the 0–5 cm soil layer. Total organic carbon (TOC) showed similar results as that of TC, where T₅ treatment had 13.15 and 13.35 % higher TOC over the T₇ at 0-5 and 5-15 cm depths, respectively. Similarly, ZT treatments with and without residue retention (R) had higher proportion of labile carbon pools in bulk soil as well as aggregates (macro and micro-aggregates) than T₇ treatments at both depths. The mean weight diameter (MWD) and proportion of macro and microaggregates were significantly higher in ZT (R) treatments than in CT. The ZT plots had higher macroaggregate associated C than CT plots in the 0–5 and 5–15 cm soil layers, respectively. At both depths, the T₅ treatment had significantly higher macro-aggregate associated C (27.10 and 29.49%) than the T₇ treatment. ZT (R) treatments recorded high dehydrogenase (DHA) and β -glucosidase activities in bulk soil as well as in aggregates. At 0–5 cm depth, T₁ treatment had 41.28% higher phenol oxidase activity than T₇ treatment (the lowest). In the same way, tillage and residue management practices had a significant effect on the glomalin protein and soil microbial biomass carbon (SMBC). In T₅, the treatment had 70 and 34 % higher coarse particulate organic matter (cPOM_M) and micro-aggregates within the macro-aggregates (mM) fractions than the T₇ treatment, respectively, in the top soil. Similarly, the same results were obtained in the case of intra-aggregate particulate organic matter (iPOM_{mM}). The ZT (R) plots had a higher light fraction within microagggregates

(LF_m) than the CT plots. Interestingly, irrespective of the treatments, the total C stock in iPOM_mM was higher than that in iPOM_m. In general, within the free microaggregates, the highest concentration of total C was in the iPOM_m, followed by s+c_m and m_LF fraction fractions, respectively. CT treatments had significantly higher decay rate constant (Kc) and temperature sensitivity of SOC mineralization (Q₁₀) values compared to ZT (R) treatments at both temperatures. However, Kc was higher at 37 °C compared to that at 27 °C, irrespective of treatments. Thus, adoption of CA has great potential in enhancing soil C content and C stability of soil aggregates to sustain soil health and crop production. Finally, this study suggested that treatment with ZTMz+R–ZTM+R–ZTMB+R (T₅) is so far the most effective treatment in carbon sequestration point of view.

Keywords: Conservation agriculture, C pools, soil organic C stabilization, ZT with and without residue retention, soil aggregates, macro-aggregates, microaggregates, glomalin related soil protein, dehydrogenase, β -glucosidase and phenol oxidase activities

सारांश

मृदा कार्बनिक कार्बन (SOC) महासागरीय और भौमिकीय पूलों के बाद तीसरा सबसे बड़ा कार्बन पूल है। इस पूल में मिट्टी में कार्बन जमा करने की क्षमता में सुधार किया जा सकता है। संरक्षण कृषि (CA) प्रथाएं जो फसल अवशेषों को सतह पर रखती हैं और विविध फसल प्रणाली के साथ न्यूनतम जुताई का उपयोग करती हैं, कार्बनिक पदार्थों के रूप में अधिक कार्बन जमा करती हैं। इस अध्ययन का उद्देश्य यह देखना था कि मक्का-सरसों फसल प्रणाली के तहत एक इंसेप्सोल में दीर्घकालिक संरक्षण कृषि प्रथाओं ने कार्बन पूल, कार्बन साइकलिंग एंजाइम, स्टॉक और कार्बन स्थिरीकरण, मिट्टी के एग्रीगेट्स, कार्बन खनिजकरण और तापमान संवेदनशीलता को कैसे प्रभावित किया। मक्के की कटाई के बाद आईसीएआर-आईएआरआई, पूसा, नई दिल्ली में 2010-11 से चल रहे एक संरक्षण प्रक्षेत्र प्रयोग से दो गहराई (0-5 सेमी और 5-15 सेमी) से मिट्टी के नमूने लिए गए। प्रयोग तीन डबल-क्रॉपिंग जीरो-टिल सिस्टम, दो ट्रिपल -क्रॉपिंग जीरो-टिल सिस्टम के साथ या बिना फसल अवशेष प्रतिधारण और दो पारंपरिक सिस्टम एक यादृच्छिक ब्लॉक डिज़ाइन में हैं - [T₁: ZTMz(-R)-ZTM(-R); T₂: ZTMz+R-ZTM+R; T₃: ZTMz+R+BM-ZTM+R; T₄: ZTMz(-R)-ZTM(-R)-ZTMB(-R); T₅: ZTMz+R-ZTM+R-ZTMB+R; T₆: CTMz(-R)-ZTM(-R); T₇: CTMz-CTM]। उच्चतम कुल कार्बन (TC) T₅ उपचार में दर्ज किया गया था, जो T₄ के बराबर था और 0-5 सेमी मिट्टी की सतह पर T₇ उपचार की तुलना में 11.68% अधिक था। कुल कार्बनिक कार्बन (TOC) ने TC के समान परिणाम दिखाए, जहाँ T₅ उपचार में क्रमशः 0-5 और 5-15 सेमी गहराई पर T₇ की तुलना में 13.15 और 13.35% अधिक TOC था। इसी प्रकार, अवशेष प्रतिधारण (R) के साथ और बिना ZT उपचारों में दोनों गहराई पर T₇ उपचारों की तुलना में थोक मिट्टी के साथ-साथ समुच्चय (मैक्रो और माइक्रो-एग्रीगेट्स) में अस्थिर कार्बन (लेबाइल कार्बन) पूल का अनुपात अधिक था। औसत वजन व्यास (MWD) और मैक्रो और माइक्रो-एग्रीगेट्स का अनुपात ZT (R) उपचारों में CT की तुलना में काफी अधिक था। जेडटी भूखंडों में क्रमशः 0-5 और 5-15 सेमी मिट्टी की परतों में सीटी भूखंडों की तुलना में उच्च मैक्रोएग्रीगेट संबंधित कार्बन था। दोनों गहराई पर, T₅ उपचार में T₇ उपचार की तुलना में काफी अधिक मैक्रो-एग्रीगेट संबंधित कार्बन (27.10 और 29.49%) पाया गया। ZT भूखंडों में क्रमशः 0-5 और 5-15 सेमी मिट्टी की परतों में CT भूखंडों की तुलना में अधिक मैक्रोएग्रीगेट संबंधित कार्बन था। दोनों गहराई पर, T₅ उपचार में T₇ उपचार की तुलना में काफी अधिक मैक्रो-एग्रीगेट संबंधित कार्बन (27.10 और 29.49%) था। ZT (R) उपचारों में थोक मिट्टी के साथ-साथ समुच्चय में उच्च डिहाइड्रोजनेज (DHA) और β -ग्लूकोसिडेस गतिविधियों को दर्ज किया। 0-5 सेमी गहराई पर, T₁ उपचार में T₇ उपचार (सबसे कम) की तुलना में

41.28% अधिक फिनोल ऑक्सीडेज गतिविधि थी। इसी तरह, जुताई और अवशेष प्रबंधन प्रथाओं का ग्लोमलिन प्रोटीन और मृदा सूक्ष्मजीव बायोमास कार्बन (SMBC) पर महत्वपूर्ण प्रभाव पड़ा। T₅ में, उपचार में ऊपरी मिट्टी में क्रमशः T₇ उपचार की तुलना में मैक्रो-एग्रीगेट्स (mM) अंशों के भीतर 70 और 34% अधिक मोटे कण कार्बनिक पदार्थ (cPOM_M) और माइक्रो-एग्रीगेट्स थे। इसी तरह, इंटर-एग्रीगेट पार्टिकुलेट ऑर्गेनिक मैटर (iPOM_{mM}) के मामले में भी यही परिणाम प्राप्त हुए। ZT (R) भूखंडों में CT भूखंडों की तुलना में माइक्रो-एग्रीगेट्स के भीतर उच्च लाईट अंश (LF_m) था। दिलचस्प बात यह है कि उपचारों के निरपेक्ष, iPOM_{mM} में कुल कार्बन स्टॉक iPOM_m की तुलना में अधिक था। सामान्य तौर पर, मुक्त माइक्रो-एग्रीगेट्स के भीतर, कुल C की उच्चतम सांद्रता iPOM_m में थी, इसके बाद क्रमशः s c_m और m_{LF} अंश थे। दोनों तापमानों पर CT उपचारों में, ZT (R) उपचारों की तुलना में क्षय दर स्थिरांक (K_c) और SOC खनिजकरण (Q₁₀) मूल्यों की तापमान संवेदनशीलता काफी अधिक थी। हालांकि, उपचारों के निरपेक्ष K_c 27 °C की तुलना में 37 °C पर अधिक था। इस प्रकार, मिट्टी के स्वास्थ्य और फसल उत्पादकता को बनाए रखने के लिए मिट्टी की कार्बन सामग्री और मिट्टी के एग्रीगेट्स की कार्बन स्थिरता को बढ़ाने के लिए CA को अपनाने की काफी संभावनाएं हैं। अंत में, इस अध्ययन ने सुझाव दिया कि ZTMz+R–ZTM+R–ZTMB+R (T₅) के साथ उपचार, कार्बन पृथक्करण की दृष्टि से अब तक का सबसे प्रभावी उपचार है।

मुख्य शब्द: संरक्षण कृषि, कार्बन पूल, मृदा कार्बनिक कार्बन स्थिरीकरण, ZT अवशेष प्रतिधारण के साथ और बिना, मृदा एग्रीगेट्स, मैक्रो-एग्रीगेट्स, माइक्रो-एग्रीगेट्स, ग्लोमलिन संबंधित मिट्टी प्रोटीन, डिहाइड्रोजनेज, β -ग्लूकोसिडेज और फिनोल ऑक्सीडेज गतिविधियां

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