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Toward Optimal Soil Organic Carbon Sequestration and Soil Physical Properties with Effects of Conservation tillage, Organic and Synthetic Fertilizers under RWCS in an Inceptisol: A Review

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A B S T R A C T

Sequestration of C in arable soils has been considered as a potential mechanism to mitigate the elevated levels of atmospheric greenhouse gases. We evaluated impacts of conservation agriculture on change in total soil organic C (SOC) and relationship between C addition and storage in an Inceptisol. The review study indicate the plots under zero tillage with bed planting (ZT-B) and zero tillage with flat planting (ZT-F) had nearly 28 and 26% higher total SOC stock compared with conventional tillage and bed planting (CT-B) (~5.5 Mg ha^{-1}) in the 0–5 cm soil layer. Plots under ZT-B and ZT–F contained higher total SOC stocks in the 0–5 and 5–15 cm soil layers than CT- B plots. Although there were significant variations in total SOC stocks in the surface layers, SOC stocks were similar under all treatments in the 0–30 cm soil layer. The concentration of SOC at different depths in 0–60 cm soil profile was higher under NP+FYM follow by under NP+S, compared to under CK. The SOC storage in 0–60 cm in NP+FYM, NP+S, FYM and NP treatments were increased by 41.3%, 32.9%, 28.1% and 17.9%, respectively, as compared to the CK treatment. Organic manure plus inorganic fertilizer application also increased labile soil organic carbon pools in 0–60 cm depth. The average concentration of particulate organic carbon (POC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) in organic manure plus inorganic fertilizer treatments (NP+S and NP+FYM) in 0–60 cm depth were increased by 64.9–91.9%, 42.5–56.9%, and 74.7–99.4%, respectively, over the CK treatment.

Introduction

Soil organic carbon (SOC) is the largest carbon (C) pool in terrestrial ecosystems, with the storage of over 1550 Pg globally therefore; small changes in the SOC pool may have a significant impact on climate change. The total amount of C stored in the top meter of soil is estimated to be 2,500 Pg C globally (1 Pg = petagram = 1015 g), including about 1,500 Pg of SOC, and 950 Pg C of inorganic soil C (SIC). This is about 3.3 times the amount of C in the atmospheric pool (760 Pg C) and about 4.5 times (560 Pg C) the amount of C stored in living vegetation (Lal, 2004b). The SOC pool plays an important role in the global C cycle and has a strong impact on agricultural sustainability, and environmental quality (Stevenson, 1994).

Agro-ecosystems, accounting for 10% of the total terrestrial area, are among the most vulnerable ecosystems to the global climate change due to their large carbon pool (Smit and Skinner, 2002). One-half to two-thirds of the original SOC pool have lost with a cumulative amount of 30–40tCha^{-1} in cultivated soils due to intensive farming (Lal, 2004a). Thus, adoption of a restorative management practices on agricultural soils is often required to improve the soil fertility and the environment (Lal, 2004b).

The deterioration of soil physical heath due to continuous cultivation without acceptable replenishment poses an immediate threat to soil health and environmental securities. Continuous cultivation of crops and excessive use of fertilizers is depleting the soil physical health hence; there is a need to reintroduce the age old practice of application of farmyard manure (FYM) to maintain soil fertility as well as soil health and also to supplement many essential plant nutrients for crop productivity. Balanced use of fertilizers in combination with manures is one of the best ways to prevent organic matter depletion and rapid deterioration of soil physical properties, specially soil structure (Singh *et al.,* 2007). Addition of organic matter increases soil organic carbon content, which directly or indirectly affects physical properties of soil and processes like water-holding capacity (WHC), hydraulic conductivity and bulk density (Celik *et al.,* 2004). While improvement in soil structural condition through the addition of C inputs has been profusely reported, a quantitative evaluation of soil physical properties under integrated nutrient management system. Thus, the balance and imbalanced use of nutrients through and organic manures and chemical fertilizers should be followed for the improvement of physical soil quality for sustainability. While the consequence of excessive use of mineral fertilizers adversely affected soil physico-chemical properties, which ultimately reduces the productivity as well as physical environment of soil under rice-wheat cropping system (Kakraliya *et al.,* 2017). Organic manure along with mineral fertilizer also helps to build up soil organic matter, which increases organic carbon which improves soil aggregation and its stability, reduce soil compaction, increase porosity and water holding capacity.

Soil tillage is among the important factors affecting soil properties and crop yield. Among the crop production factors, tillage contributes up-to 20% [Khurshid *et al.,* 2006] and affects the sustainable use of soil resources through its influence on soil properties [Lal and Stewart, 2013]. Reducing tillage positively influences several aspects of the soils whereas excessive and unnecessary tillage operations give rise to opposite phenomena that are harmful to soil. Therefore, currently there is a significant interest and emphasis on the shift from extreme tillage to conservation and no-tillage methods for the purpose of controlling erosion processes. During multiple tillage operations, SOM is redistributed within the soil profile and minor changes in it may affect the formation and stability of soil aggregates. The objectives of the review study were: (i) to assess the impact of conservation tillage based practices manure and inorganic fertilizers on rice-wheat system on soil physical properties and aggregate–associated C content; (ii) to know the C–stabilization rate in different tillage practices in rice-wheat cropping systems, and (iii) to assess the effect of organic and inorganic fertilizers with residue retention, and tillage practices on soil organic carbon pools and soil residual fertility.

Changes in SOC by tillage, N-fertilizer and manure application

SOC is an important index of soil quality and health and is an important component of the soil fertility of farmlands, as well as being the core of soil quality and function (Pan and Zhao, 2005). SOC content can directly affect soil fertility and crop yield, and greatly affects the formation and stability of the water-stable soil aggregate structure (Cai *et al.,* 2009).

West and Post (2002) found the average relative increased SOC stock was 0.57 ± 0.14 Mg C ha^{-1} yr^{-1}, with 75% of the studies showing increased SOC stocks. Gollany *et al.,* (2006) found that increased SOC storage in the fine organic matter fraction with reduced tillage ranged from 0.16 to 0.18 Mg C ha^{-1} at N fertilizer rates of 15 and 180 kg N ha^{-1} under long-term wheat-fallow system, compared to moldboard plowed soils. Angers and Eriksen-Hamel, (2008) also found there was a small, but significant increase in total SOC stocks under no-tillage, but all of this increase was observed in the upper 10 cm. This can be explained by residue burial to a greater depth due to tillage and shows that limited depth of soil sampling could result in over- or under-estimation of SOC stocks. Gupta Chaudhary *et al.,* (2014) reported that conservation tillage (both RT and ZT) caused 21.2%, 9.5%, 28.4%,13.6%,15.3%,2.9% and 24.7% higher accumulation of SOC in >2mm, 2.1–1.0 mm,1.0–0.5 mm, 0.5–0.25 mm,0.25–0.1 mm,0.1–0.05 mm and <0.05 mm sized particles than conventional tillage (T_1 and T_2) treatments. Direct seeded rice combined with zero tillage and residue retention (T_6) had the highest capability to hold the organic carbon in surface (11.57g kg^{-1}soil aggregates) and retained least amount of SOC in sub-surface (9.05 gkg^{-1} soil aggregates) soil. In comparison with transplanted rice (TPR), direct seeded rice (DSR) enhanced 16.8%, 7.8%, 17.9%,12.9%, 14.6%,7.9% and 17.5% SOC in>2mm, 2.1–1.0mm,1.0–0.5 mm,0.5–0.25mm, 0.25–0.1mm, 0.1–0.05 mm and <0.05 mm sized particles.

Aulakh *et al.,* (2013) also found that in 0 - 5 cm layer of CT system, T_2, T_3 and T_4 treatments increased TOC content from 3.84 gkg^{-1} in control (T_1) to 4.19, 4.33 and 4.45 gkg^{-1} without CR, and to 4.40,4.83 and 5.79 gkg^{-1} with CR (T_6, T_7 and T_8) after 2 years. The corresponding values of TOC content under CA system were 4.55 gkg^{-1} in control to 4.73, 4.79 and 5.02 gkg^{-1} without CR and to 4.95, 5.07 and 5.30 gkg^{-1} with CR. After 4 years of these treatments, there was further improvement in TOC content from 1% to 26% in CT and none to 19% in CA treatments. Liu *et al.,* (2013) reported that the distribution of SOC with depth was dependent on the use of various fertilizers. The highest SOC concentration was obtained for 0–20 cm depth and decreased with depth for all treatments. The SOC concentration in 0–20, 20–40 and 40–60 cm depths increased significantly by farmyard manure or straw application. At the 0–20 and 20–40 cm soil depths, SOC was highest in NP+FKM followed by NP+S and FYM treatments and the least in CK treatment. However, the topsoil (0–20 cm) had the maximum levels of cumulative SOC storage in the 1 m soil depth for the CK, N, NP, FYM, NP+S and NP+FYM treatments, accounting for 24%, 23%, 27%, 30%, 31% and 31%, respectively. At the 20–40 cm and 40–60 cm soil layers, the SOC stocks of the NP, FYM, NP+S and NP+FYM treatments were significantly higher by 17%, 21%, 25% and 37% and 5.3%, 8.1%, 7.3% and 11%, respectively, than that of the CK. The differences of SOC storage between different treatments were not significant in the 60–80 cm and 80–100 cm soil layers. SOC storages were significantly different between fertilization treatments in the 0–100 cm profile. Compared with the CK treatment, SOC storages of the NP+FYM, NP+S, FYM and NP treatments within the 0–100 cm soil depth were increased by nearly 30, 24, 20 and 12%, respectively.

Zheng *et al.,* (2018) also found that the SOC content for different treatments decreased with soil depth with significantly higher content in the topsoil than in the sub-layer. At the 0–10cm depth, the mean SOC varied with treatment, with the conservation tillage (ST and NT) significantly higher than conventional tillage (CT). At 10-30cm, especially, the ST treatment was significantly higher. At 20–30cm, the mean SOC from greatest to smallest was ordered ST>MP>CT>NT, with ST significantly higher than other treatments. Xin *et al.,* (2015) revealed that soil OC concentrations were increased with residue retention, and the increases varied with soil depth (Table 1). In the 0–10 cm layer, soil OC concentrations of the treatments with crop residues were 6% higher than that of the treatments without residues. Soil OC concentrations under 4TS (plowing every 4 years with residue) and NTS were 18 and 22% higher than that of T across the three years. In the 10–20 cm layer, soil OC concentration under TS (plowing every year with residue) was 7% higher than that of T across the three years, but there was no significant difference between NTS and NT.

Zhang *et al.,* (2016) reported that increasing the rate of fertilizer application could increase SOC levels linearly by enhancing residue accumulation (Fig.1). The fertilizer N application rates are 1.5 and 2.0 times of the baseline level, the average annual SOC changes are 1.37 and 1.55 times that of the baseline level, respectively (Fig.1). In contrast, reduced N-fertilizer and no N-fertilizer application would significantly reduce the SOC. The average annual SOC changes were −33 and−330 kg C $ha^{-1}yr^{-1}$ for the 0.5FL and NFL scenarios, respectively and the corresponding SOC changes are 142% and 522% lower than the baseline scenario. Increased mineral N fertilizer rate that increases C sequestration often has adverse effects on emissions of greenhouse gases (e.g., N_2O) (Desjardins *et al.,* 2001).

The application of crop residues without supplemental fertilizer N will not generally meet crop N demand, and thus may lead to yield decline. However, the return of crop residues over the long term may lead to a buildup of readily mineralized organic soil N, and potentially a reduction in N fertilizer requirements. Soil type, crop residue management and tillage practices and climatic conditions may also have an important impact on SOC storage in agricultural systems with a diversity of best management practices (Ogle *et al.,* 2015; Fujisaki *et al.,* 2018).

Ogle *et al.,* (2015) observed that greater increases in SOC upon conversion from conventional tillage to no-till in tropical moist (23% increase) > tropical dry (17% increase) > temperate moist (16% increase) > temperate dry (10% increase) climates. Hence, agricultural management impacts on SOC storage and dynamics can be sensitive to climatic conditions in different agro-regions which may be further driven by plant-derived C inputs, particularly in tropical croplands with a greater influence on SOC priming (Lenka *et al.,* 2019). Figure 2 showed that it is evident that N is released from crop residues in both organic and inorganic forms; most organic N is not available to plants directly. While a small portion of crop residue N may be mineralized immediately after application, a larger portion will become immobilized in the soil microbial pool, later to be mineralized or transformed into other SOM pools as microbial byproducts (Kopittke *et al.,* 2018; Sarker *et al.*, 2018b). This mineralized N may be taken up by crop plants, recycled in the microbial biomass, or lost from the soil-plant system via leaching, erosion, or in gaseous form. A portion of the crop residue N may enter the complex SOM pools or organo mineral fractions (Lehmann and Kleber, 2015).

SOC fractions

Gue *et al.,* (2016) reported that compared with CT treatments, NT treatments did not affect SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly increased the SOC concentration of bulk soil in the 0−5 cm soil layer. In comparison with NS treatments, S treatments had not significant effects on SOC concentration of bulk soil in the 5−20 cm soil layer, but significantly enhanced the SOC concentration of bulk soil in the 0−5 cm soil layer. In the 0−5 cm soil layer, NT treatments significantly increased SOC concentration by 5.8%, 6.8%, and 7.9% of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate, respectively, compared with CT treatments. NT treatments significantly increased MBC of bulk soil, >0.25 mm and <0.25 mm aggregates by11.2%, 11.5% and 20.0%, respectively, compared with CT treatments. DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under NT treatments were 15.5%, 29.5%, and 14.1% higher than those under CT treatments, respectively. In comparison with NS treatments, S treatments significantly increased SOC concentrations of bulk soil by 12.8%, >0.25 mm aggregate by 11.3%, and <0.25 mm aggregate by 14.1%. In addition, MBC of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate under S treatments were 29.8%, 30.2%, and 24.1% higher than those of NS treatments, respectively. S treatments exhibited 25.0%, 37.5%, and 23.2% higher DOC concentrations of bulk soil, >0.25 mm aggregate, and <0.25 mm aggregate compared with NS treatments, respectively. In the 0−5 cm soil layer, there were significant interactions of tillage and straw returning on SOC concentration of >0.25 mm and <0.25 mm aggregates, MBC of bulk soil and <0.25 mm aggregate, and DOC concentration of >0.25 mm aggregate.

Anantha *et al.,* (2018) also found that the magnitude of carbon pools extracted under a gradient of oxidizing conditions was as follows: $C_{VL} > C_{LL} > C_{NL} > C_L$ constituting about 41.4, 20.6, and 19.3 and 18.7%, respectively, of the TOC (Table 2). However, the contribution of VL, L and LL pools to SOC was 51.2, 23.1 and 25.5%, respectively. While active pool ($C_{VL} + C_L$) constituted about 60.1%, passive pool ($C_{LL} + C_{NL}$) represented 39.9% of the TOC. Among the treatments, 100% NPK+FYM (44.4%) maintained a proportionately higher amount of soil C in passive pools. With an increase in the dose of fertilization, on average, C allocation into passive pool was increased (33.0, 35.3, 40.7% and 39.3% of TOC under control, 50% NPK, 100% NPK and 150% NPK treatments, respectively).

Carbon restoration in soil profile

The stability of soil aggregates determines the ability of the aggregates to resist exogenic action and to remain stable when exposed to changes in the external environment. In addition, aggregates are known to closely correlate with the soil erodibility and appear to play an important role in maintaining the stability of soil structure. Almost 90% of SOC exists in the form of aggregates in the topsoil. Therefore, study of intra-aggregate C is of great significance to the influence of human disturbance on SOC (Zheng *et al.,* 2013.) Naresh *et al.*, (2015) reported that the highest SOC concentration of 5.8 g kg^{-1} in the surface layer (0–15 cm) was observed in F_4 followed by that in F_6 (5.4 g kg^{-1}) treatment. All plots treated with organic amendments contained higher SOC concentration in the surface and sub-soil compared with those not receiving any organics. The SOC concentration also improved with the application of F_3 (5.1 g kg^{-1}) and F_5 (4.9 g kg^{-1}). In contrast, the SOC concentration increased with the application of organic materials even in the sub-soil. The mean pro-file SOC concentration increased from 2.2 g kg^{-1} in F_1 to 4.4 g kg^{-1} in F_4. However, no increase in SOC concentration was observed in treatment F_2 (Table 3). It is widely recognized that the use of organic manures and compost enhances the SOC concentration more than does the use of the same amount of nutrients applied as chemical fertilizers.

Awanish (2016) revealed that the greater variations among carbon fractions were observed at surface layer (0-5 cm). F_1= very labile, F_2 =labile, F_3= less labile and, F_4=non-labile. At this depth, C fraction in vertisols varied in this order: $F_4>F_1>F_2=F_3$. Below 5 cm, the carbon fraction was in the order: $F_4>F_1>F_3>F_2$. For 15-30 cm depth it was in the order $F_4>F_1>F_2>F_3$. At lower depth, almost similar trend was followed as that of 30-45 cm. Regardless of tillage system, contribution of different fractions of carbon (C) to the TOC varied from, 33 to 41%; 9.30 to 30.11%; 8.11 to 26%; 30.6 to 45.20% for very labile, labile, less labile and non-labile fractions, respectively at 0-5 cm depth. For subsurface layer (5-15cm), contribution of different fractions to the TOC varied from 27.8 to 40%; 7.80 to 12.40%; 11.11 to 19.0% 38.0 to 50.0% for very labile, labile, less labile and non-labile fraction, respectively. In general, C contents decreased with increasing depth, mainly for very labile faction (F1) which was contributing around 40% or more in surface and surface layers (0–5 and 5–15 cm) as compared to deeper layers (15–30 and 30–45 cm). Moreover, less labile and non-labile fractions contribute more than 50% of TOC, indicating more recalcitrant form of carbon in the soil.

Das *et al.*, (2016) revealed that among the OOC fractions, C_{VL} in the 0–7.5, 7.5–15 and 15–30 cm soil depths was in the range 1.02–2.51, 0.72–2.09 and 0.58–1.15g kg^{-1} respectively, with corresponding mean values of 1.71, 1.43 and 0.90 g kg^{-1}. At the 0–7.5 cm soil depth, the lowest C_{VL} was seen in the unfertilized control treatment (1.02 g kg^{-1}) and CVL increased significantly under IPNS treatments, with particularly high values (2.51 g kg^{-1}) under the NPK + GR + FYM treatment. This treatment also had the highest C_{VL} values at the 7.5–15 and 15–30 cm depths (2.09 and 1.15 g kg^{-1} respectively). At 7.5–15 and 15–30 cm soil depths, the lowest C_{VL} values were observed under the NPKZn treatment (0.72 and 0.58 g kg^{-1} respectively) rather than in the unfertilized control. Compared with uncultivated soil, the CVL content was lower under control or NPKZn treatments, but was invariably greater under treatments using combinations of FYM, GR or SPM with NPK fertilizers. The percentage change in CVL over uncultivated soil varied from–38% to 109% at different depths. However, the C_{NL} content at the 0–7.5, 7.5–15 and 15–30cm soil depths varied, with values in the range 7.23–10.07, 6.73–8.63 and 4.30–6.40 g kg^{-1} respectively, and corresponding mean values of 7.99, 7.73 and 5.39 g kg^{-1}. Averaged across treatments, the C_{NL} content at the 0–7.5 and 7.5–15 cm depths was similar, but decreased significantly at the15–30 cm soil depth. Averaged across soil depths, CNL content under the NPK + CR and NPK + GR + FYM treatments (7.99 and 7.63 g kg^{-1} respectively) were significantly higher than in the other treatment groups. Compared with uncultivated soil, the change in C_{NL} under different nutrient supply options was inconsistent, although C_{NL} content increased under the NPK+CR treatment by 25–33% at the 0–7.5 and 7.5–15 depths. Considering overall mean values across soil depths and nutrient supply options, the abundance of these four OOC fractions was in the order C_{NL}(7.04 g kg^{-1}) > C_L (2.02 g kg^{-1})> C_{VL} (1.35 g kg^{-1}) > C_{LL} (0.75 g kg^{-1}).

Ghosh *et al.,* (2018) observed that SOC accumulation rates in plots under NPK+FYM and NPK in the 0–90 cm soil profile were ~745 and 529 kg ha^{-1} yr^{-1}. However, C sequestration rates in the 0–90 cm soil profile for NPK and NPK+FYM treatments were only ~167 (31% of the accumulated SOC) and 224 kg $ha^{-1}yr^{-1}$, respectively.

Interestingly, NPK, 150% NPK and NPK+FYM treated plots had similar recalcitrant C contents in the said soil profile, but had significantly different C accumulation rates.

Nearly 54% of the accumulated SOC and 34% of the sequestered SOC under NPK+FYM plots were observed within deep soils (30–90 cm soil layer), implying role of INM on C sequestration in deep soils. Zheng *et al.,* (2018) observed that the SOC storage in macro-aggregates under different treatments significantly decreased with soil depth. However, no significant variation was observed in the micro-aggregate-associated C storage with depth. SOC storage increased with aggregate size from 1–2 to > 2mm and decreased with a decrease in aggregate size. The SOC storage in macro-aggregates of all sizes from 0-30cm depth was higher in the ST treatment than in other treatments. From 30-60cm, trends were less clear. SOC storage in micro-aggregates showed the opposite trend, with significantly higher levels in the CT treatment from 0-30cm, and no significant differences between treatments below this depth.

Soil physical properties affected by tillage, organic and synthetic fertilizers

Zhang *et al.,* (2007) reported no-tillage practices improve soil aggregation and aggregate stability. The increase in aggregate stability contributes to increased soil water infiltration and resistance to wind and water erosion. Macro-aggregate stability (> 250 μm diameter) is particularly sensitive to changes in management practices (Zibilske and Bradford, 2007). The loss of macro-aggregate occluded organic matter is a primary source of C lost due to changes in management practices (Jiao *et al.,* 2006). Continuous cropping with reduced fallow frequency and no-tillage has a positive effect on macro-aggregate formation and stabilization (Mikha *et al.,* 2010). Liu *et al.,* (2013) also found that an application of manure and fertilizer significantly affected soil bulk density (BD) to a depth of 40 cm. The addition of FYM or straw (FYM, NP+FYM and NP+S) treatments decreased soil bulk density significantly in comparison to that in control plots in all the layers. However, the decrease was more in upper soil layers (0–20 and 20–40 cm) than in the lower layers (40–60, 60–80 and 80–100 cm). Similar was the case with NP treatment, where BD was lower than that in CT treatment at 0–20 and 20–40 cm depths.

Pant and Shri Ram (2018) also found that in 0-60 cm soil layers, the bulk density was significantly lower in 100% NPK + FYM over other treatments. The balanced application of NPK decreased the bulk density in all the soil depths. Irrespective of soil depths, the control plot invariably showed higher bulk density. The soil receiving 100% NPK fertilizers with FYM recorded significantly higher hydraulic conductivity, water holding capacity and mean weight diameter in soils of all four depths, respectively as compared to control and all other fertilizer treatments (Fig. 3a, 3b; and 4a).

Whalen *et al.,* (2003) revealed that the proportion of WSA >4 mm was greater in soils receiving compost than soils that did not receive compost and there were fewer WSA <0.25 mm in compost-amended than un-amended soils (Fig. 4b). In addition, there were fewer WSA between 0.25 and 1mm in compost amended than un-amended soils. The MWD of aggregates increased linearly with increasing rates of compost application. Aggregation is influenced by the chemical composition of organic residues added to soils. Organic residues that decompose quickly may produce a rapid but temporary increase in aggregation, whereas organic residues that decompose slowly may produce a smaller but long lasting improvement in aggregation (Sun *et al.,* 1995).

Bhattacharyya *et al.,* (2008) observed that an increments in hydraulic conductivity up to 45-cm depth after 8 years of farmyard manure application in a silty clay loam soil of India. Saturated hydraulic conductivity (Ksat) values in all the studied soil depths were significantly greater under ZT than those under CT (range from 300 to 344 mm/day) and the unsaturated conductivity {k(h)} values at 0–75 mm soil depth under ZT were significantly higher than those computed under CT at all the suction levels, except at %10, %100 and % 400 kPa suction. Abid and Lal (2009) observed that significantly higher infiltration in no till (I= 71.4 cm) than conventional till (I = 48.9cm) on silt loam soil. Tillage and residue management also influenced cumulative and steady-state infiltration. Retention of the straw on the surface also significantly influenced the cumulative infiltration and steady state infiltration (104 mm, 73 mm h^{-1}) as compared to residue removal (84 mm, 54mm h^{-1}).

Singh *et al.,* (2014) reported that saturated hydraulic conductivity (Ks) values for various depths of soils were largely higher under ZT than that of CT; however, differences were significant to a depth of 0.10m. The magnitude of increase in Ks of surface 0.05 m depth was highest in loam (51%) followed by sandy loam (40%) and clay loam (38%) soil. Since Ks is a function of the size and continuity of pores, therefore, higher accumulation of soil organic carbon and less soil disturbance in ZT might have promoted the formation of macro pores responsible for higher water transmission as compared to CT practices. Naresh *et al.,* (2015) also found that the infiltration rate was consistently highest with an overall average of 84.7mm h^{-1} (raised bed), lowest at 50.3 mm h^{-1} in conventional tillage (puddling), and intermediate 55.7; 62.2 mm ha^{-1} in rotary tillage and zero tillage. Infiltration after permanent wide raised beds and zero till flat beds increased with time, indicating improvement in soil structure, as also supported by soil aggregation.

Naresh *et al.,* (2016) reported that mean soil bulk density in the 0- to 20-cm soil layer of the FIRB with residue retention and ZT with residue retention plots was 12.4 and6.8% lower, respectively, than the CT plots. In addition, the FIRB treatment had significantly lower soil bulk density in the 0- to 10- and 10- to 20-cm soil layers than CT by 14.3 and 12.8%, respectively. The changes in bulk density were mainly confined to top 10-15 cm layer.

Xin *et al.,* (2015) observed that the proportion of macro-aggregates was larger than that of the other aggregate fractions (Fig. 4a). Macro-aggregates accounted for 38–64, 48–66, and 54–71% of the total soil mass in the 0–5, 5–10, and 10–20 cm soil depths, respectively. The corresponding proportions of the silt +clay fraction were 3–7, 2–6, and 1–5%, respectively. Proportions of macro-aggregates were increased with reduction of soil tillage frequency (Fig. 5a). For the 0–5 cm soil depth, treatments NT and 4T had significantly higher mass proportions of macro-aggregates (36 and 23%, respectively) than that of treatment T. In the 5–10 cm layer, the proportions of macro-aggregates of NT and 4T were 24 and 15% higher than that in T, respectively. In the 10–20 cm depth, the proportions of macro-aggregates of NT and 4T were 21 and 14% higher than that of T. However, the MWD (mean weight diameter) and GMD (geometric mean diameter) values were significantly increased with the reduced frequency of plowing at all depths (Fig. 5b). In the 0–5 cm layer, compared with T, values of MWD under 4T and NT were increased by 41 and 68%, respectively. Values of MWD under NT in the 5–10 and 10–20 cm depths were increased by 41 and 28% as compared to that under T. The highest GMD value appeared in NTS, while the lowest appeared in T across all soil depths. Additionally, residue retention had pronounced positive effects on MWD and GMD. The average MWD values among crop residue treatments were 30, 15 and 14% higher than the corresponding treatments without crop residues in the 0–5, 5–10, and 10–20 cm depths, respectively.

Bandyopadhyay *et al.,* (2010) also found that straw incorporation helps in the formation and stability of aggregates through increase in microbial cell and microbial excretions and its decomposition products released during the death of microorganisms. Soils receiving rice straw along with NPK had more water stable macro-aggregates (74.2%), higher aggregate stability (73.24%), mean weight diameter (0.89 mm) and geometric mean diameter (0.89 mm) than the control treatment (Table 4). There is a meager variation in structural indices due to paddy rice straw incorporation but influences the soil hydro-physical environment in rice–rice system in clayey soil. It increased the hydraulic conductivity, porosity and water retention capacity.

Singh *et al.,* (2014) reported that a significant increase in bulk density was observed in surface 0.05 m in sandy loam and 0.10 m in both loam and clay loam soils (Fig.6a). Saturated hydraulic conductivity increased significantly only to a depth of 0.10 m but with varying magnitudes. Increase in magnitude in surface 0.05 m layer was highest in loam (51%) followed by sandy loam (40%) and clay loam (38%) soil (Fig. 6b). Although ZT increased water retention and aeration porosity but increase in field water capacity was significant to a deeper depth (0.15 m) in clay loam soil (Fig.6b).

Table.1 Soil OC concentration in the 0-10 and 10-20 cm depths in 2011-2013

Treatment	Soil OC in 2011 ($g\ Kg^{-1}$)		Soil OC in 2012 ($g\ Kg^{-1}$)		Soil OC in 2013 ($g\ Kg^{-1}$)	
	0-10cm	10-20cm	0-10cm	10-20cm	0-10cm	10-20cm
TS	6.89±0.55d	6.82±0.18a	7.62±0.35bc	6.41±0.18b	7.73±0.16b	6.52±0.18b
2TS	7.35±0.76cd	6.68±0.45	7.47±0.23bc	6.55±0.37	7.57±0.17bc	6.67±0.28ab
4TS	8.00±0.44b	6.75±0.32a	8.21±0.30a	6.67±0.35ab	8.31±0.23a	6.78±0.35ab
NTS	8.16±0.32a	5.86±0.84c	8.59±0.48a	6.92±0.34a	8.69±0.22a	7.03±0.25a
T	7.10±0.62d	6.26±0.39b	6.81±0.41d	6.08±0.51c	6.91±0.22d	6.19±0.24c
2T	6.61±0.62d	6.35±0.66ab	7.20±0.41d	6.51±0.62b	7.30±0.24c	6.62±0.21ab
4T	7.87±0.72bc	6.95±0.96a	7.82±0.25b	6.34±0.37bc	7.92±0.27b	6.46±0.20bc
NT	7.53±0.93c	5.88±0.69c	8.30±0.36a	6.57±0.69b	8.40±0.22a	6.68±0.16ab

Table.2 Oxidisable organic carbon fractions (very labile, labile less labile and non-labile) in soils (g kg^{-1}) at different layers (cm)

Treatment	Very labile C				Labile C			
	0-15	15-30	30-45	Total	0-15	15-30	30-45	Total
Control	3.6 ±0.5^{c}	1.4 ±0.3^{b}	1.3±0.2^{a}	6.3±0.4^{b}	2.4±0.3^{a}	1.0±0.2^{a}	0.8±0.4^{a}	4.2±0.6^{a}
50% NPK	4.6 ±0.3^{bc}	2.1± 0.7^{ab}	1.5±0.1^{a}	8.1±0.9^{a}	1.7±0.4^{ab}	0.9±0.5^{a}	0.7±0.2^{a}	3.3±0.7^{a}
100% NPK	4.4 ±0.3^{bc}	2.3± 0.2^{a}	1.4±0.5^{a}	8.0±0.7^{a}	1.8±0.4^{ab}	0.8±0.5^{a}	0.6±0.3^{a}	3.2±0.8^{a}
150%NPK	5.0 ±0.2^{ab}	2.6± 0.2^{a}	1.5±0.1^{a}	9.0±0.3^{a}	1.2±0.3^{b}	0.7±0.2^{a}	0.9±0.2^{a}	2.8±0.4^{a}
100% NPK+ FYM	4.8 ±0.2^{ab}	2.0 ±0.2^{ab}	1.3±0.3^{a}	8.1±0.2^{a}	1.9±0.3^{ab}	0.7±0.2^{a}	0.7±0.2^{a}	3.4±0.2^{a}
FYM	5.9 ±1.3^{a}	2.2 ± 0.2^{a}	1.4±0.3^{a}	9.5±1.6^{a}	2.5±0.9^{a}	0.7±0.3^{a}	0.7±0.3^{a}	3.9±0.9^{a}
Fallow	4.2 ±0.7^{bc}	1.5 ± 0.5^{b}	0.7±0.3^{b}	6.3±0.8^{b}	2.2±1.0^{ab}	0.7±0.3^{a}	1.0±0.4^{a}	4.1±1.1^{a}
	Less labile C				Non labile C			
Control	1.5±0.3^{c}	0.6±0.4^{c}	0.4±0.0^{c}	2.6±0.7^{b}	1.2±0.5^{b}	1.2±0.3 ^{a}	0.2±0.2^{b}	2.6±0.5^{b}
50% NPK	1.8±0.1^{c}	0.4±0.1^{c}	0.5±0.2^{c}	2.7±0.1^{ab}	1.2±0.9 ^{b}	1.7±0.8 ^{a}	0.7±0.4^{ab}	3.5±1.8^{ab}
100% NPK	2.5±0.3^{ab}	0.8±0.1^{bc}	1.1±0.2^{ab}	4.4± 0.1^{b}	1.3±0.6 ^{b}	1.5±0.6 ^{a}	0.5±0.2^{ab}	3.3±1.0^{ab}
150%NPK	2.6±0.2^{a}	0.9±0.1^{bc}	0.4±0.2^{c}	3.9±0.1^{b}	1.4±0. ^{b}	1.5±0.2 ^{a}	0.8±0.1^{a}	3.7±0.3^{ab}
100% NPK+ FYM	2.7±0.6^{a}	1.5±0.6^{a}	1.4±0.1^{a}	5.6±0.7^{a}	2.0±0.8 ^{b}	1.3±0.1 ^{a}	0.3±0.3^{ab}	3.5±0.7^{ab}
FYM	1.9±0.7^{bc}	1.7±0.2^{a}	1.0±0.2^{b}	4.5±0.7^{ab}	3.7±1.3^{a}	1.0±0.2 ^{a}	0.5±0.5^{ab}	5.1±1.9^{a}
Fallow	1.5± 0.3^{c}	1.3±0.7^{ab}	0.9±0.4^{b}	3.8±1.2^{bc}	2.1±0.2 ^{b}	1.4±0.7^{a}	0.4±0.2^{ab}	3.9±0.9^{ab}

Table.3 Changes in soil organic carbon (SOC) (g kg^{-1}) concentration in soil after 12 yr of tillage crop establishment and fertilization

Soil Depth (cm)	Initial (2001)	F_1 Control	F_2-50% RDF	F_3-100% RDF	F_4-100% Organic (FYM)	F_5-50% RDF + 50% (foliar)	F_6-50%Organic (FYM)+ 50% RDF	F_7-Farmers practice	Mean
0-15	4.7±0.26	3.7±0.19^{Dbt}	3.9±0.18^{Db}	5.1±0.21^{Ab}	5.8±0.28^{Aa}	4.9±0.^{23Ca}	5.4±0.26^{Ba}	4.8±0.23^{Cb}	4.8±0.23^{Cb}
15-30	4.5±0.25	3.1±0.18^{Cc}	3.2±0.17^{Ca}	4.6±0.19^{Cb}	5.5±0.23^{Aa}	4.1±0.21^{Cb}	5.2±0.22^{Ba}	3.3±0.18^{Cc}	4.2±0.20^{Cc}
30-60	3.1±0.19	2.1±0.13^{Cd}	2.4±0.13^{Fa}	3.3±0.18^{Cc}	5.1±0.21^{Ab}	3.1±0.18^{Cc}	4.5±0.19^{Bb}	2.8±0.15^{Bc}	3.3±0.17^{Cc}
60-80	2.3±0.13	1.1±0.07^{Cd}	1.9±0.11^{Aa}	2.8±0.15^{Cd}	3.4±0.19Ac	2.3±0.14^{Ea}	2.7±0.15^{Ca}	1.9±0.11^{Ca}	2.3±0.13^{Ca}
80-100	1.4±0.09	0.9±0.05^{Cc}	1.1±0.07^{Db}	1.6±0.10^{Ab}	2.3±0.13^{Ad}	1.5±0.09^{Bb}	1.9±0.12^{Cb}	1.2±0.07^{Cb}	1.5±0.09^{Bb}
Mean	3.2±0.18	2.2±0.12^{Cc}	2.5±0.13^{Db}	3.5±0.18^{Cb}	4.4±0.21^{aA}	3.2±0.17^{Cc}	3.9±0.19^{Bb}	2.8±0.15^{Bc}	-

**Different letters within columns are significantly different at P=0.05 according to Duncan Multiple Test (DMRT) for separation of means.

Fig.1 Annual SOC change from 2001 to 2019 under different management practices

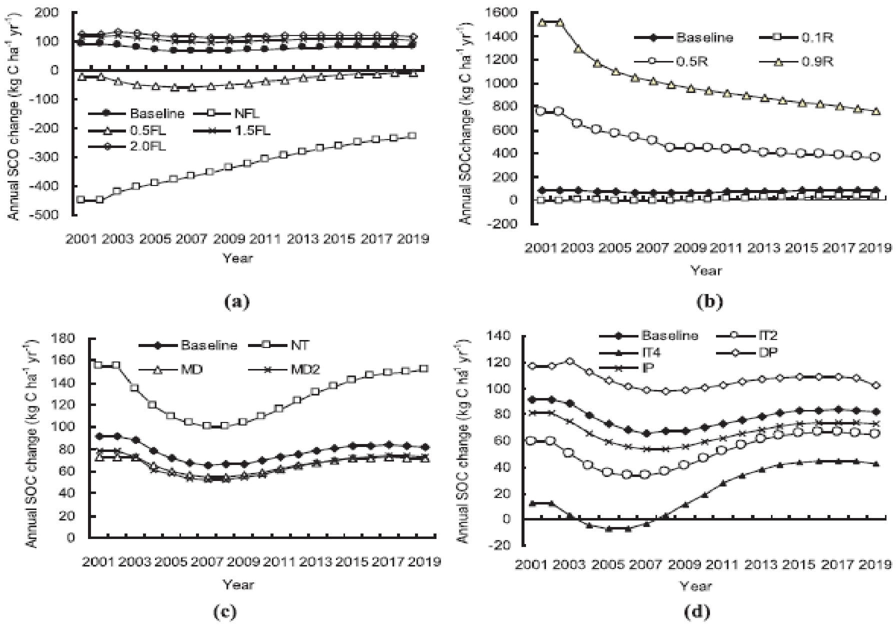


Fig.2 Schematic diagram showing different pathways of nitrogen in crop residue amended soils

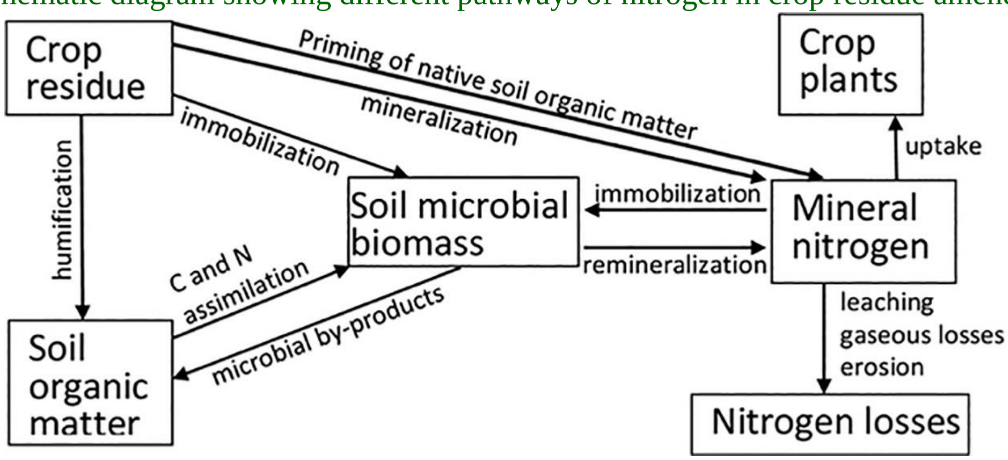


Fig.3a Effect of organic and inorganic fertilizers on bulk density after rice and wheat crop

Fig.3b Effect of organic and inorganic fertilizers on water holding capacity after rice and wheat crop

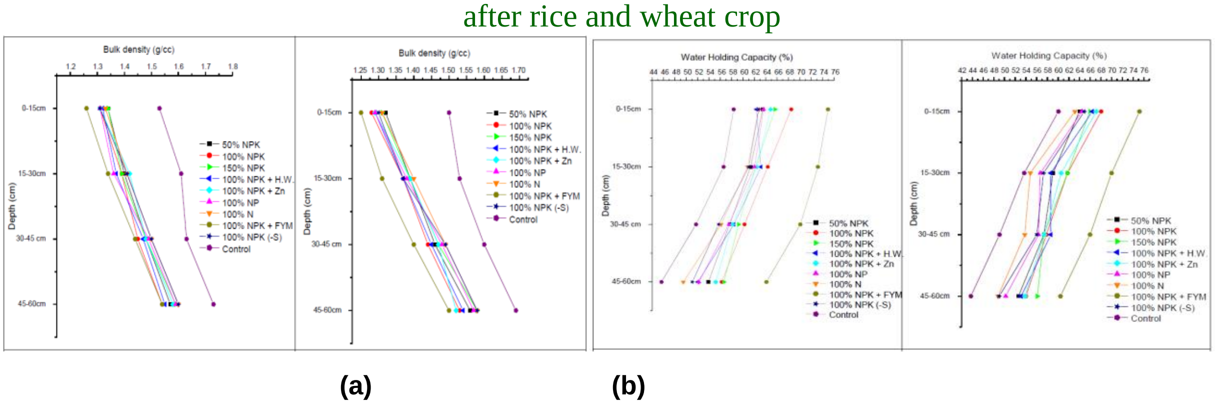
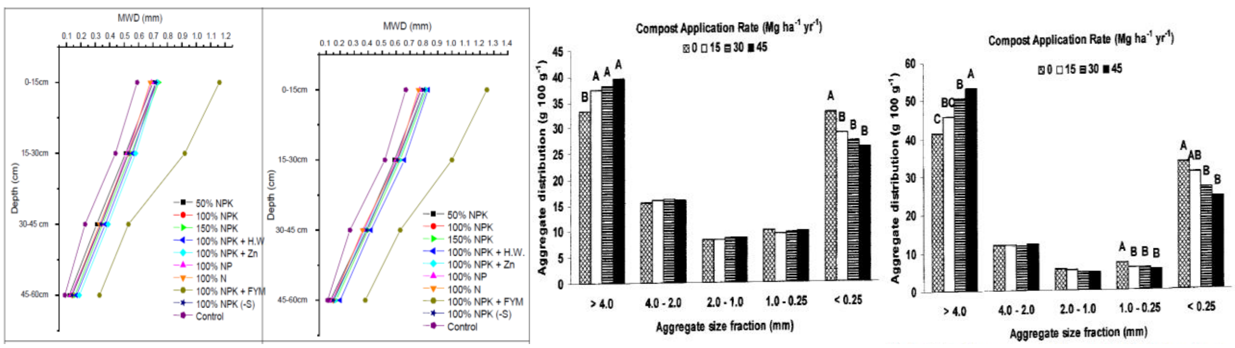
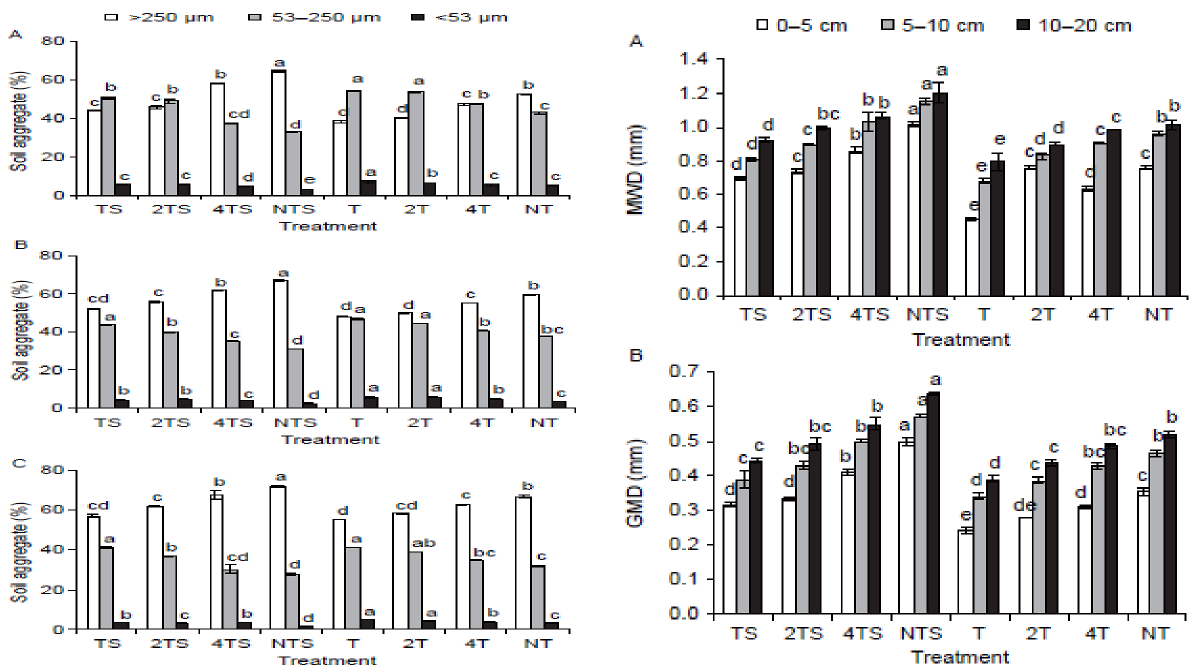


Fig.4a Effect of organic and inorganic fertilizers on mean weight diameter after rice and wheat crop; **Fig.4b** Effect of compost applications on the distribution of water-stable aggregates



(a) (b)

Fig.5a Soil aggregate distribution in the 0-5 cm (A), 5-10 cm (B) and 10-20 cm (C) depths under different tillage systems



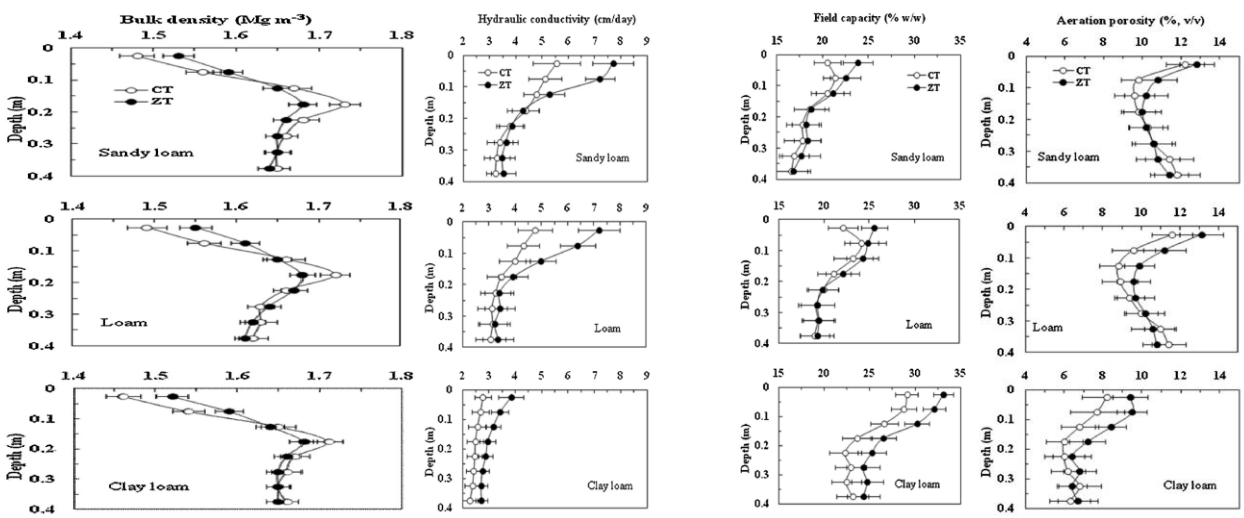
(a) (b)

Table.4 Effect of rice straw incorporation on structural indices and distribution of particle size (0–0.15 m depth) in rice–wheat system after 21 years

					Mechanical Analysis		
Treatment	WSMA(%)	AR	AS(%)	MWD(mm)	Sand(%)	Silt(%)	Clay(%)
Native	76.8[a]	3.31[a]	76.75[a]	1.57[a]	12.1	32.0	55.9
Control	41.0[c]	0.60[d]	39.30[c]	0.60[d]	11.1	32.0	56.9
NPK	63.2[b]	1.72[c]	63.20[b]	0.61[d]	11.1	30.0	58.9
NPK+FYM	75.6[a]	3.10[a]	75.05[a]	1.11[b]	13.1	30.0	56.9
NPK+PS	74.2[a]	2.88[b]	73.24[a]	0.89[c]	17.1	34.0	48.9
NPK+GM	72.4[a]	2.62[b]	71.80[a]	0.88[c]	11.1	38.0	50.9

WSMA, water soluble macro-aggregate; AR, aggregate ratio of macro and micro; MWD, mean- weight diameter.
Note: Superscript of a, b, c and d are the degrees of significance in DMR Test

Fig.6a Soil bulk density at various depths of texturally different soils under conventional (CT) and zero (ZT) tillage; **Fig.6b** Saturated hydraulic conductivity, field water capacity and aeration porosity of various depths of texturally different soils under conventional (CT) and zero (ZT) tillage.



(a) **(b)**

Zheng *et al.*, (2018) reported that stability of water-stable soil aggregates, as measured by *GMD*, *MWD*, and E_{LT} varied with soil layers under different treatments. For the ST and NT treatments, *GMD* decreased with an increase in depth, but for the MP and CT treatments *GMD* increased initially with a subsequent decrease with depth. At the 0–10 and 10–20cm depths, ST exhibited significantly higher values of *GMD* than for the other treatments, and at each depth from 20-50cm, ST was significantly higher than at least one other treatment. *MWD* was higher at 0-20cm than at the 20-60cm depths for the ST and NT treatments but was opposite for the MP and CT treatments. In the top 20cm of soil, the ST and NT treatments outperformed the MP and CT treatments. The mean for the overall 0–60cm depth showed an inter-treatment comparison of ST>NT>MP>CT, with significant differences between ST/NT and CT. However, E_{LT} under different tillage treatments varied with soil depth, increasing with depth for the ST and NT treatments, but initially increasing and then decreasing for the MP and CT treatments. E_{LT} was significantly higher for the CT treatment at depths of 0–10, 20–30, 30–40, and 50-60cm, and was on average higher in the CT and MP treatments.

In conclusion, conventional system of tillage in rice–wheat cropping system was found to develop a compaction pan beneath the usually tilled layer of 0.15 m in different textured soils under rice cultivation in while the ZT system used in wheat helped in reducing this sub-soil compaction. Soil physical properties were improved as a consequence of decreased disturbance and crop residue cover on the surface in ZT system. ZT practice resulted in increased organic carbon, field water capacity and aeration status in soils. Lower subsoil bulk density and reduced water dispersible silt + clay contents resulted in increased saturated hydraulic conductivity, and infiltration rate favorable for better soil physical properties.

The application of optimal dose of NPK (100%) along with FYM in rice-wheat cropping system improved the soil physical properties i.e., improved aggregate stability, decrease in bulk density, increased saturated hydraulic conductivity and improved soil water-holding capacity of soil in comparison to application of NPK fertilizers alone. The physical properties play a vital role for the nutrient turnover and long-term productivity of the soil which are enhanced by balanced application of nutrients and manure. Continuous cropping of rice-wheat with imbalanced nutrient management declined the physical properties of soil. SOC concentrations and storage were highest in surface soil and depth interval down to 60 cm under NP+FYM and NP+S, below which concentrations did not change with depth. At the same time, on average the estimate of soil C storage to 60 cm depth was higher than that for soil C accumulated to 20 cm depth and to 40 cm depth, respectively. The estimate of soil C accumulation to 60 cm depth was more effective than that for soil C accumulated to 20 cm depth and to 40 cm depth. NP+FYM were the most efficient management system for sequestering SOC. A large amount of C was also sequestered in soil under NP+S treatment. Organic and synthetic fertilizers also had a positive effect on the redistribution of SOC among the particle-size fractions, with obvious depletion of SOC in fine particles and pronounced enrichment in macro-aggregates. However, the enrichment factors of SOC in macro-aggregates of all treatments were>1 and that of micro-aggregates were<1 in both soil layers, indicating C sequestration in macro-aggregates and C depletion from micro-aggregates. Hence, the enrichment factor of SOC is a better indicator than the labile: recalcitrant C to assess C sequestration within aggregates. Thus, returning crop residue to the soil or adding farmyard manure on the soil surface is crucial to improving the SOC level. The location of C stabilization in aggregate size fraction from the added organics might be dependent on the amount and the nature of bio-chemicals present in organics and their array with mineral particles and will help to enhance the capacity of carbon sequestration.

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