Impact of Residue Incorporation on Soil Carbon Storage, Soil Organic Fractions, Microbial Community Composition and Carbon Mineralization in Rice-wheat Rotation – A Review

R. K. Naresh[1], M. Sharath Chandra[1*], Aryan Baliyan[2],
Shakti Om Pathak[2] , Pradeep Kumar Kanaujiya[3], B. Naveen Kumar[4],
O. V. S. Thenua[5], and Pradeep Kumar Singh[1]

[1]*Department of Agronomy, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh., India.*
[2]*Department of Soil Science and Agricultural Chemistry, Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, Uttar Pradesh., India.*
[3]*Department of Agronomy, Acharya Narendra Deva University of Agriculture and Technology, (Kumarganj) Ayodhya, Uttar Pradesh, India.*
[4]*Department of Soil Science & Agricultural Chemistry, Sri Konda Laxman Telangana State Horticultural University, Hyderabad, India.*
[5]*Department of Agronomy, A. S. College, Lakhaoti, Bulandshahr, C.C.S University, Meerut, Uttar Pradesh, India.*

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This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Review Article

ABSTRACT

In agroecosystems, straw return is a useful management strategy for increasing soil fertility and crop productivity. The total organic carbon (TOC), dissolved organic C (DOC), and microbial biomass C (MBC) contents all increased significantly when compared to the no straw return (N)

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Corresponding author: E-mail: sharathagrico@gmail.com;

and straw return (S) treatments, while the easily oxidizable C content remained same. The S treatment resulted in a 28–52 percent increase in soil light fraction, light fraction organic C, and particle organic C over the N treatment. When compared to the N treatment, crop straw return increased total phospholipid fatty acid (PLFA), bacterial biomass, and actinomycete biomass by 52, 75, and 56 percent, respectively. Under short-term crop straw return, MBC and TOC were the two key determinants determining microbial populations. In comparison to residue removal, residue retention (RR) enhanced SOC storage by 11.3 percent. SOC content and contribution of macro-aggregates in the 0-20 cm depth and micro-aggregates in the 20-40 cm depth rose significantly when no-tillage and straw returns were used together. When no-tillage with straw returning (NTS) was used instead of CT, SOC content, mean weight diameter (MWD), geometric mean diameter (GMD), and fractal dimensions (FD) rose by 25%, 21%, 19%, and 12%, respectively, in the 0-20 cm depth. Soil micro-aggregates were greater in the 20-40 cm depth after CTS treatment. In the 0-20 cm depth, the percentages of macro- and micro-aggregates increased by 60% and 40%, respectively, under NTS. MWD, GMD, > 5, 2-5, 1-2, and 0.25-0.5 mm aggregates all had a positive linear relationship with the SOC. Microbial biomass C (MBC) was considerably enhanced by 20.0 percent when compared to conventional tillage (CT) and no-tillage (NT), but total organic C (TOC), dissolved organic C (DOC), readily oxidizable C (EOC), and SOC of aggregates were not affected. MBC increased by 18.3% and SOC content of 2–1-mm aggregate increased by 9.4% when residue was returned. Total PLFAs grew by 9.8%, while fungal biomass increased by 40.8 percent, thanks to NT. Total PLFAs, bacterial biomass, fungal biomass, F/B, and MUFA/STFA were all increased by 31.1, 36.0, 95.9, 42.5, and 58.8 percent, respectively, while microbial stress was reduced by 45.9%. Wheat straw return had a considerable impact on the bacterial community in the soil, but not on the fungus community. It increased the relative abundance of the bacteria phylum Proteobacteria and the fungal phylum Zygomycota, while decreasing the relative richness of the bacterial phylum Acidobacteria and the fungal phylum Ascomycota. It increased the relative abundance of nitrogen-cycling bacterial taxa including Bradyrhizobium and Rhizobium, among others. This diversity includes bacteria, cyanobacteria, archaea, planctomycetes, and -proteobacteria, as well as endophytes. The system's intricacy and dynamic nature necessitate in-depth research on the three-part interactions between plants, microorganisms, and the soil-water environment.

1. INTRODUCTION

Soil organic carbon (SOC) is widely recognised as the largest terrestrial carbon (C) reservoir, and its importance in soil fertility, crop productivity, and climate change mitigation has garnered considerable attention [1]. Fertilization is a significant determinant of cropland SOC quantities because it can alter the equilibrium between primary C inputs and C decomposition [2]. Soil microorganisms are the primary decomposers of SOC and key drivers of soil nutrient cycling in agricultural ecosystems [3]. Understanding the mechanisms of SOC decomposition by microorganisms is crucial to developing fertilisation strategies that maintain and improve soil C buildup and fertility.

On a worldwide scale, soil organic C (SOC) plays a critical role in controlling soil ecology and C cycle processes [4]. Soil management strategies are regarded critical for preserving soil quality [5], and the plough layer can have a significant impact on the composition and stability of SOC [6]. Because of the disruption of soil aggregates and increased soil aeration, conventional tillage (CT) may reduce SOC content and accelerate SOC oxidation rate [7]. According to long-term research experiments, switching from conventional tillage (CT) to no-tillage (NT) methods can sequester around 57 14 g C m^{-2} yr^{-1}, with the SOC sequestration rate projected to peak within 5-10 years following conversion [8]. Furthermore, Six et al. [9] found that when NT plots were compared to CT plots, the SOC content increased by around 325 113 kg C ha^{-1} yr^{-1}. Continuous long-term no-tillage systems at the surface layers may only provide an incomplete view of changes in the soil profile [10]. However, the magnitude of NT impacts on SOC content can vary, and this variation is influenced by regional and environmental factors [11], allowing for a more detailed examination of NT effects on soil properties.

Crop residue returning (RR), or returning aboveground and belowground biomasses to the field after harvesting, is a globally recognized

management strategy for improving soil quality and productivity. RR can help to improve the structure of the soil [12] Increase crop output and farming system production capacity [13,14] in a sustainable way by boosting systematic biodiversity, boosting SOC sequestration capacity, and partially replacing fertilizer input [15]. To preserve soil quality, high crop output, and sustainability, RR must be implemented in a scientific and sensible manner. Tillage procedures [16], returning mode [17], meteorological conditions, and duration are all elements that can affect RR [18,19]. When compared to conventional tillage, Sun et al. [20] found that conservation tillage increased SOC storage. Similarly, Chalise et al. [21] reported that mulch retention could be more helpful than alternative returning strategy for increasing soybean output and soil water storage (RR without cover crops). The researchers noted that increasing the amount of residue increased C sequestration in a 12-year experiment [22].

Soil organic carbon is a collective term for carbon in humus, animal and plant residues, and microorganisms formed in the soil by microbial action; it is the primary source of carbon nutrients required for plant and biological life in the soil and constitutes important physical and chemical properties of the soil, and its content in the soil is greatly affected by the type and abundance of soil microbial life. Soil organic carbon regulates the physical, chemical, and biological properties of soil and improves soil stability; its accumulation and transformation can affect soil water, fertiliser, gas, heat, and biochemical processes, as well as the absorption and release of substances, directly or indirectly [23], and its content in soil is closely associated with soil quality and agricultural productivity [23]. Sun et al., [24] reported that as a consequence, it is critical to investigate changes in the pool of soil organic carbon in order to ensure the agroecosystem's long-term viability.

Soil bacteria are crucial components of agroecosystems, as they are the primary drivers of soil organic matter and nutrient cycling [25]. Soil bacteria have been chosen as an essential indicator of soil quality because of their quick reaction to fertilisation [26]. For example, the shift in denitrifying bacteria communities caused by variations in black soil characteristics was directly linked to denitrification capacity under different fertilisation regimes [27]. After a long period of time, such a shift may result in changes in soil function and quality. Nutrient cycling, soil

stability, and organic matter decomposition are all aided by soil microbes. To successfully manage agricultural systems, soil microbiological and biochemical features must be taken into consideration in soil resource inventories. As a reason, it's critical to keep a focus on the bacterial communities in the soil to ensure its long-term viability.

Understanding the impacts of straw return on the soil organic carbon pool in the rice-wheat rotation system is therefore critical for ensuring long-term agricultural sustainability. The aims of this review paper were to (a) assess the impacts of different straw returning measures on the soil organic carbon pool, as well as the effects on soil bacterial composition and diversity in the rice-wheat rotation system; (b) to quantify the impacts of tillage methods and straw return on soil TOC, MBC, DOC, and EOC contents in the rice-wheat rotation system and (c) To improve soil quality and deepen cognitions to alter field management strategy to improve SOC storage, it is required to adapt the rice-wheat rotation system's straw returning technology to improve soil labile organic C for a specific soil, climate, and cropping system.

2. STRAW RETURNING ON SOIL CARBON STORAGE

According to Jin et al. [28], soil microorganisms play a critical role in decomposing re-turned straw, and any factors that change soil microbial species, quantity, or activity would have an impact on returned straw decomposition. The C/N ratio has a big impact on how quickly crop straw decomposes. The suitable C/N ratio for soil microorganisms to degrade organic materials is around 25–30:1. For every 00 g of straw digested by microbes, roughly 0.8 g of nitrogen is required, and the appropriate C/N ratio for soil microorganisms to degrade organic materials is roughly 25–30:1; While the C/N ratio of straw from Gramineae crops is typically higher than this value, microbial decomposition of returned rice and wheat straw requires the original nitrogen in the soil, which causes competition for nutrients between microorganisms and crops and slows the decomposition rate of returned straw (Fig.1a). Furthermore, in the early stages of decomposition, straw has more soluble organic matter and a greater C/N ratio, and as it decomposes, the soluble matter and C/N ratio steadily decrease. As a consequence, nitrogen fertilizer should be applied early in the straw-returning process. An appropriate application of

nitrogen fertilizer can increase the available nitrogen content of the soil, reduce the soil C/N ratio, promote soil microorganism growth and activity, increase cellulase and other hydrolase activities, inhibit oxidase activity, and promote the decomposition of returned straw; however, an excessive application of nitrogen fertilizer will inhibit the activity and chemical stability of lignin-decomposing enzymes in the soil, thereby delaying the promote the decomposition of returned straw.

Soil is implicated in the carbon (C) and nitrogen (N) biogeochemical cycles, and hence is a critical compartment for climate regulation, either by emitting GHGs or by sequestering C. (Fig. 1b). Soil holds a lot of carbon: the first metres of mineral soils include between 1,500 and 2,400 Pg of organic carbon [29,30]. This is roughly three to four times the amount of carbon in plants (450–650 PgC) and twice to three times the quantity of carbon in the atmosphere (829 GtC). Furthermore, peat soils and permafrost contain around 1,500 Pg of carbon. CO_2 is released from soils as a result of the biological degradation of plant litter and soil organic materials. It represents a flux of 118.7 PgC per year when combined with vegetation respiration, which is less than the photosynthetic flux (123 PgC per year), turning land into a sink. When organic materials disintegrate in oxygen-depleted environments, such as rice paddies or flooded areas, methane (CH_4) is created. Rice production emits 24–30 Pg C per year, accounting for approximately half of all emissions from animals. The global nitrogen cycle includes nitrous oxide (N_2O), which is connected to various forms of nitrogen (e.g., organic, ammonia, nitrate). The microbial decomposition of organic and mineral nitrogen in soil produces N_2O, which is often boosted in moist conditions. The main anthropic

source is emissions from the soil, which are estimated to be between 1.7 and 4.8 Tg N_2O per year.

Residue return duration had a big impact on SOC storage, according to Wang et al. [31]. Short-term RR (1–5 years) increased SOC storage by 10.7%, whereas medium-term RR (6–10 years) increased SOC storage by 9.3%. The effect of long-term RR (>10 years) was the strongest, accounting for 13.5 percent of the total (Fig. 2). Maize, wheat, and rice residues significantly boosted SOC storage by 9.7%, 10.6%, and 9.2%, respectively; however, the return of various crop residues had no effect on SOC storage.

Furthermore, the cropping pattern was linked to SOC storage. SOC storage increased extremely significant 16.7% following 6–10 years of RR without crop rotation, while SOC storage grew modestly 8.1 percent after 6–10 years of RR with crop rotation. Crop rotation had a reduced influence on the rise in SOC storage in >5 years of RR adoption as compared to production without crop rotation. In fields without crop rotation, SOC sequestration rate decreased as returning duration beyond ten years, indicating that the soil had reached its maximum capacity to store carbon. This suggested a condition known as "C saturation." SOC storage increased considerably in single cropping systems under RR 12.6 percent, regardless of the cropping system. In double-cropping systems, crop growth used more SOC, resulting in a considerable increase in SOC storage of 10.1 percent under RR. Under RR, maize, wheat, and rice cultivation exhibited similar effects on SOC storage, increasing by 10.5 percent, 10.3 percent, and 12.4 percent, respectively.
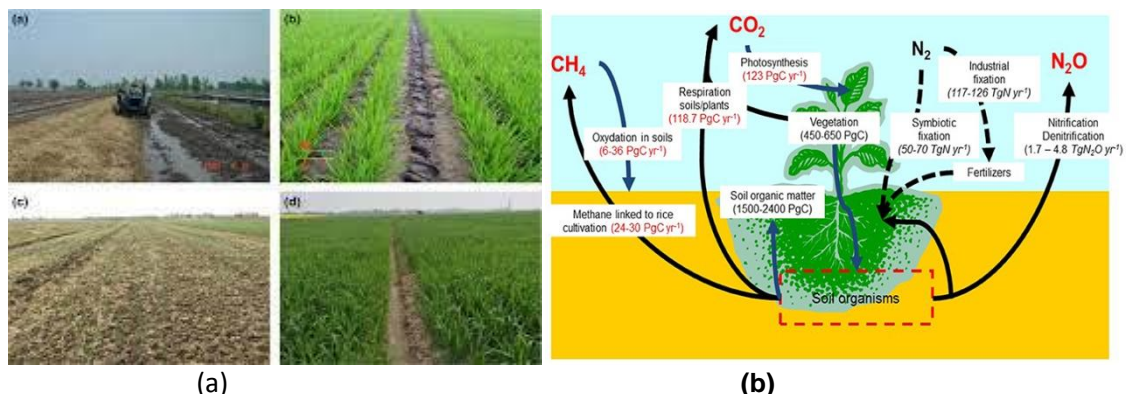

Fig. 1a. Wheat straw returning to the rice field (a), rice growth with wheat straw (b), rice straw returning to the rice field (c), and wheat growth with rice straw (d)
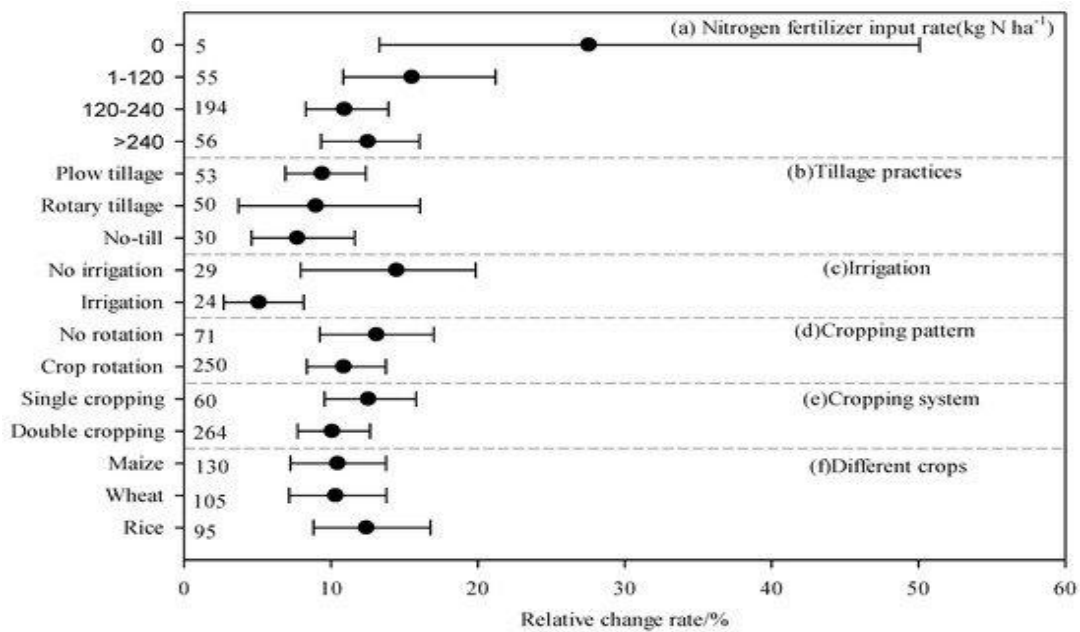**Fig.1b. Soil and GHGs fluxes (adapted from Ciais et al., [29]**

Fig. 2. The pace at which SOC storage changes in response to residue retention. Other RR techniques include residue chopping, equally integrating, and burying, among others; MR stands for mulching retention; OSCS stands for one-time return in single-cropping systems; ODCS stands for one-time return in double-cropping systems; TDCS stands for two-time return in double-cropping systems

In both soil depths, tillage and straw returning treatments showed significantly higher SOC content than the other treatments (Fig. 3). Under the straw returning plots NTS and CTS treatments, the 0-20 cm had a higher SOC content. In a year-by-year comparison, NTS treatment outperformed CT, with results increasing from 15.7 to 18.8 g kg^{-1} (2013), 15.8 to 19.0 g kg^{-1} (2014), and 16.2 to 20.2 g kg^{-1} (2015) in the 0-20 cm depth (Fig. 3). Zhang et al. [16] found the same outcome in NT or NTS therapy. However, in the 20-40 cm depth, a varied trend was detected, with values ranging from 3.2 to 5.0 g kg^{-1} (2013), 3.9 to 5.2 g kg^{-1} (2014), and 4.8 to 6.1 g kg^{-1} (2015). (Fig. 3). During the three years, the substantial interactive effect of straw returning and tillage treatments on SOC content was achieved at 0-20 cm for the entire soil profile (0-40 cm), with the trend being NTS > CTS > CT > NT. In comparison to the other three treatments, the average SOC content suggests that NTS greatly raised the SOC content in the 0-20 cm depth. According to Rajan et al. [32] and Xin et al. [33], the major variations between NT and CT occur in the soil's upper top layer. Increased SOC concentration in the surface layer of straw returning plots NTS and CTS treatments may be linked to higher straw residue inputs, resulting in greater SOC retention in surface soil [7,34]. The higher SOC content could be attributed to the interaction of tillage and straw returning, which results in a better conversion efficiency of straw residue C to SOC [7,35].

According to Banerjee et al. [36], the non-puddled soil organic carbon was at its highest (0.76 percent) at 292 DAT in the FYM treatment (Fig. 4a). The first wheat crop was harvested at the same time. SOC increased with this treatment throughout the growth of the first wheat crop, then fell slightly before increasing again during the second wheat crop. In non-puddled no-tilled soil, a similar tendency was seen (Fig. 4a). However, in this situation, the greatest value in the green manure and 100 percent organic supply treatments was 0.69 percent at 259 DAT. Banerjee et al. [36] observed that after transplantation, the SOC of the puddled-tilled and puddled-no-tilled sites increased, with high values reported for 364–475 days (Fig. 4b). The FYM and green manure treatments both showed an increase in SOC. It's also clear that the organic carbon content of surface soil increased slightly during the second rice crop's growth. In the FYM treatment, the maximal value of SOC was 0.81 percent (Fig. 4b).
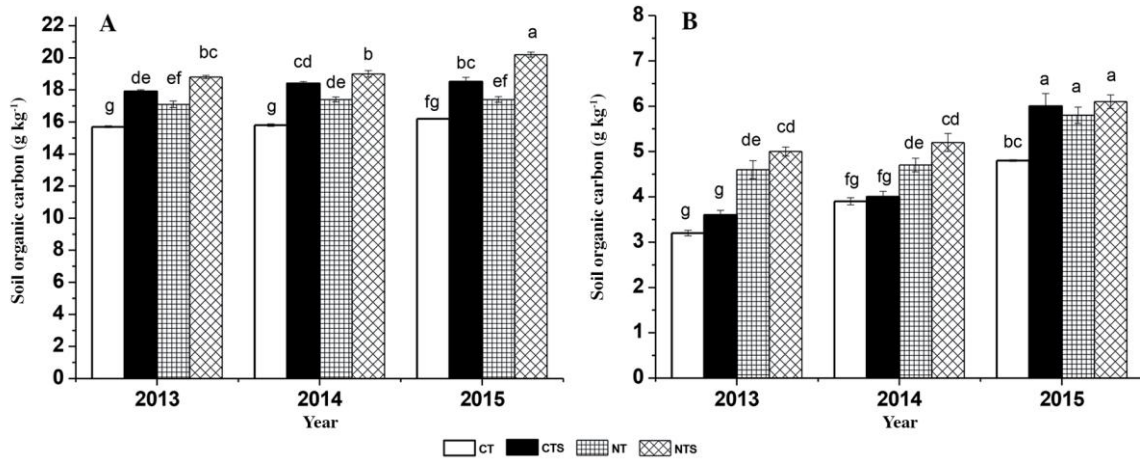
Fig. 3. Organic carbon content of soil in various treatments
A: 0-20 cm and B: 20-40 cm. CT: Conventional tillage, CTS: conventional tillage with straw returning, NT: no-tillage, NTS: no-tillage with straw returning
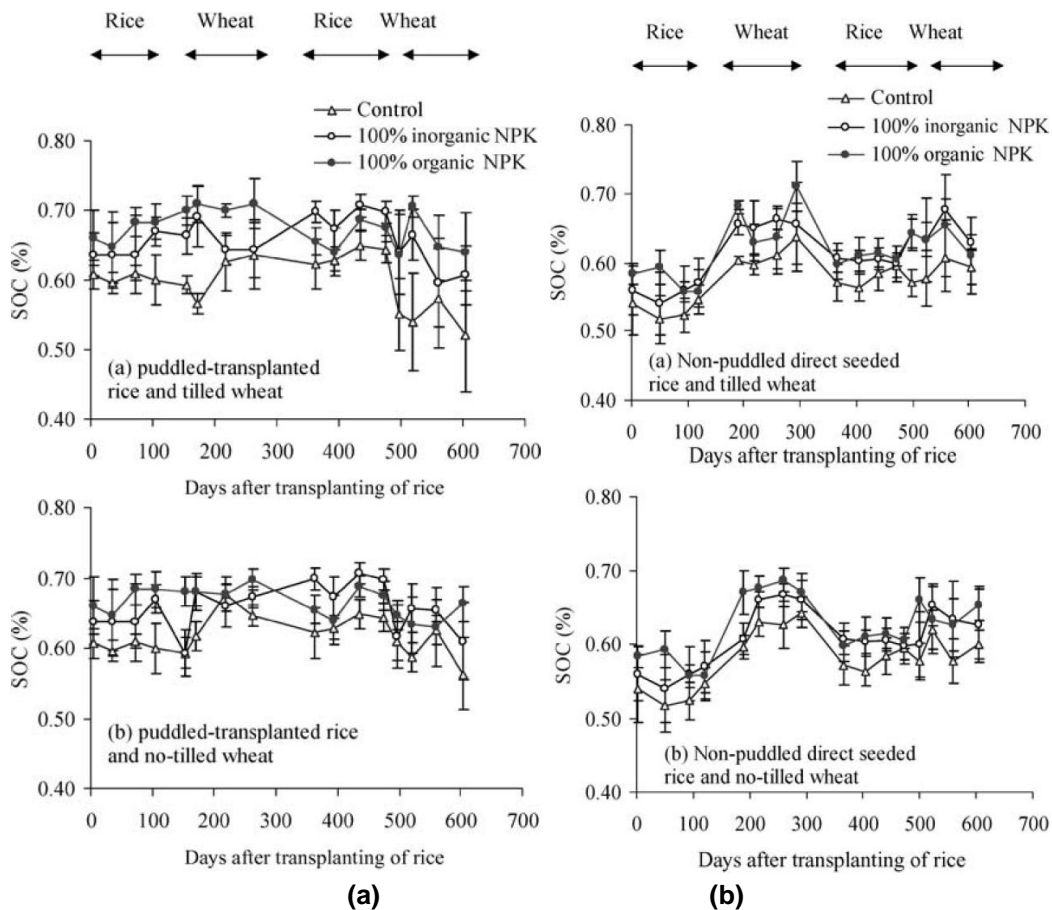

Fig. 4a. Soil organic carbon (SOC) content in (a) puddled-transplanted rice and tilled wheat and (b) puddled-transplanted rice and no-tilled wheat
Fig. 4b. Soil organic carbon (SOC) content in (a) non-puddled direct-seeded rice and tilled wheat and (b) non-puddled direct-seeded rice and no-tilled wheat

3. STRAW RETURNING ON SOIL ORGANIC CARBON FRACTIONS

In all treatments, Shen et al. [37] found that DOC and POXC content increased as aggregate particle sizes shrank. In large-size macro-aggregates, DP and NT treatments had significantly higher DOC content than RT treatment (Fig. 5a). In the DP treatment, however, micro-aggregates had much lower DOC concentrations. The maximum POC content was found in 1–0.25 mm macro-aggregates in the RT, DP, and SS treatments, while it was 5–2 mm in the NT treatment. In small macro- and micro-aggregates, the DP, SS, and NT treatments resulted in decreased POC content. In large macro-aggregates, only the NT treatment resulted in considerably greater POC. SS and NT treatments had lower MBC content in all particle size aggregates than the RT treatment. MBC content was higher in the DP treatment in the 5–2mm and 2–1mm aggregates, but lower in the 1–0.25 mm and 0.25 mm aggregates than in the RT treatment. In terms of POXC content, the DP treatment resulted in significantly greater POXC content across the line. While under the SS therapy, the readings were much lower. In comparison to RT, the NT treatment had higher POXC in macro-aggregates but lower values in micro-aggregates. Tillage encourages macro-aggregate turnover and organic carbon mineralization in macro-aggregates, which lowers the stability of plant-derived SOC in micro-aggregates [38]. Under all tillage treatments, however, the level of SOC in micro-aggregates was higher than in macro-aggregates. Furthermore, in the RT, SS, and NT

treatments, there was a trend that SOC content increased significantly as aggregate particle sizes decreased (Fig. 5b). However, there was no significant difference in organic carbon content among four sizes of macro-aggregates in the DP treatment. In aggregates with a diameter of >5 mm, 2–1 mm, and 0.25 mm, the NT treatment had considerably higher organic carbon content than the RT treatment. In aggregates larger than 5 mm, organic carbon content in the DP treatment was higher than in the RT treatment, while it was lower in 1–0.25 mm and 0.25 mm aggregates. Furthermore, in 1–0.25 mm and 0.25 mm aggregates, SS treatment exhibited lower organic carbon content than RT treatment.

In the 0–5, 5–10, and 10–20 cm soil layers, Dai et al. [39] reported that WSOC concentration was higher in NPKS$_2$ than in NPK, and CK in all soil layers (Fig. 6a). In all soil levels, WSOC ranged from 0.53 to 1.04 percent of total SOC, and in the 0–10 cm layer, NPKS$_2$ had a greater WSOC/SOC than the other treatments. In all soil layers, NPKS$_2$ had larger HWSOC, EOC, and POC concentrations than NPK and CK (Fig. 6b, c, and e). HWSOC comprised 2.83 to 4.25 % SOC, whereas EOC made up 17.34 to 33.81 % and POC made up 21.49 to 38.26 percent. MBC content in NPKS$_2$ was higher than in NPK in the 0–5, 5–10, and 10–20 cm soil layers, and CK in all soil layers (Fig. 6d). Similarly, LFOC content in NPKS$_2$ was higher than in NPK in the 10–20 and 20–30 cm soil layers, and CK in all soil layers (Fig. 6f). MBC comprised 2.21 to 2.72 percent of total SOC, while LFOC made up 7.37 to 17.60 percent of total SOC.
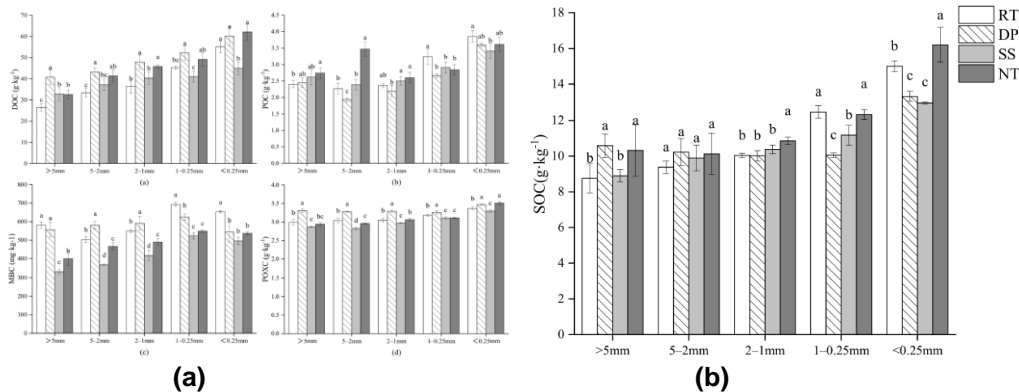

Fig. 5a. Effects of tillage on DOC, POC, MBC, and POXC content in aggregates. Shown is the data for: (a) DOC content in aggregates; (b) POC content in aggregates; (c) MBC content in aggregates; (d) POXC content in aggregates
Fig. 5b. Effects of tillage on SOC content in aggregates. Different filling types refer to different treatments. RT: rotary tillage, DP: deep plowing, SS: subsoiling, NT: no-tillage

4. STRAW RETURNING ON MICROBIAL COMMUNITY COMPOSITION

The activities of soil microbes are inextricably linked to the mineralization and decomposition of soil organic matter, the formation of humus, and the transformation and transport of nutrients [40]. Returning straw to the soil can enhance soil structure, increase organic matter content, and provide a healthy habitat for microorganism development and reproduction, as well as sufficient carbon and nitrogen supplies and energy, resulting in an increase in the species, quantity, and activity of soil microorganisms [22]. Bacteria account for 70–90% of all soil microorganisms and are the most active factor in soil, playing an important role in the decomposition of cellulose in straw [41]; an extracellular enzyme secreted by fungi is the main microbial enzyme used for straw decomposition [42]; and actinomycetes play a key role in the decomposition of lignin in straw (The researchers Lou, Liang, et al. [43] and Lou, Xu, et al. [22] found that returning straw to the soil increased the quantity of bacteria, fungus, and actinomycetes substantially.
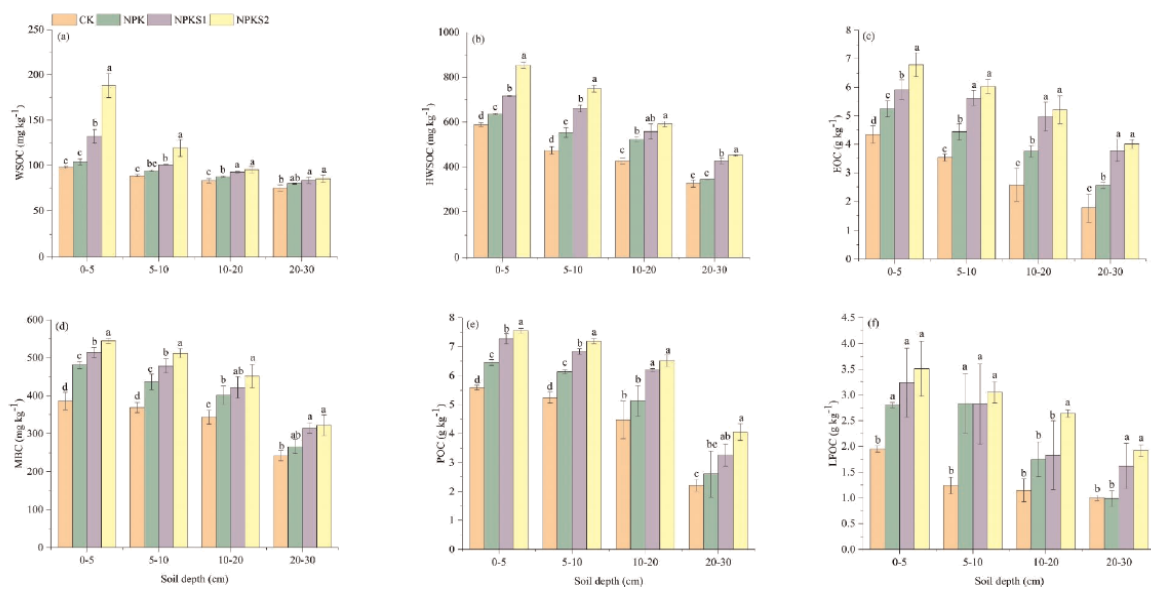

Fig. 6 The effects of straw incorporation on labile organic C fractions (WSOC, water-soluble organic C; HWSOC, hot-water soluble organic C; EOC, easily oxidizable C; MBC, microbial biomass C; POC, particulate organic C; LFOC, light fraction organic C) in the soil layers of 0–5, 5–10, 10–20, and 20–30 cm. Different letters mean significant difference at 0.05 level. CK: unfertilized control; NPK: N, P, and K fertilizers; NPKS$_1$: wheat straw incorporated at a moderate rate of 3000 kg ha^{-1} plus NPK fertilizers; NPKS$_2$: wheat straw incorporated at a high rate of 6000 kg ha^{-1} plus NPK fertilizers
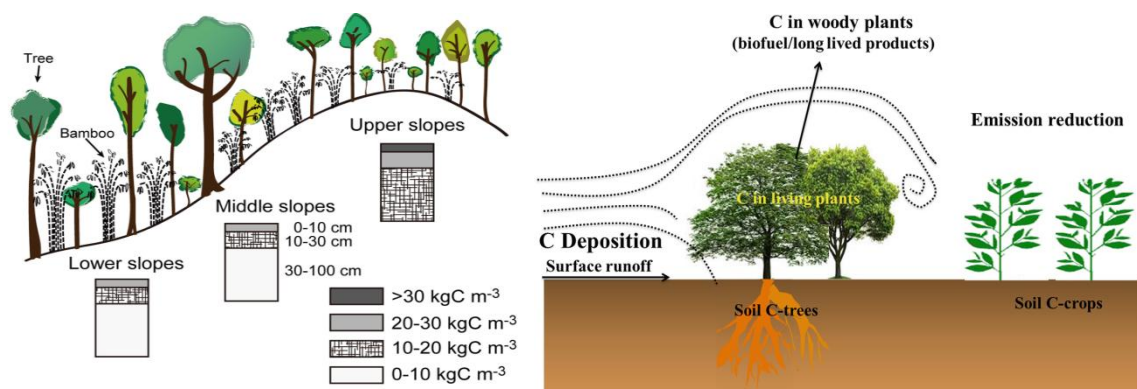

Fig. 7. Slope position and Soil carbon densities

Han et al. [44] observed that Proteobacteria, Chloroflexl, Actinobacteria, Acidobacteria, Gemmatimonadetes, Bacteroidetes, Firmicutes, and Planctomycetes were the dominant phyla across four treatments, accounting for more than 88 percent of the bacterial sequences from each treatment soil sample (Fig. 8a). The phyla Ascomycota, Motierellomycota, Rozellomycota, and Basidiomycota accounted for more than 84 percent of the fungal phyla in the four treatments. Unclassified fungal phyla made up more than 9% of the total. Straw-return treatments had a major impact on the phyla Ascomycota, Motierellomycota, Rozellomycota, and Basidiomycota. Furthermore, Ascomycota and Basidiomycota were shown to be considerably greater in MmRi than in CK, M_0R_i, or M_iR_i treatments.

According to Dai et al. [45], returning straw to the soil can boost soil nitrogen mineralization while reducing heterotrophic bacteria activity, resulting in enhanced fungal growth. In the study, returning straw resulted in a considerable increase in Ascomycota and Basidiomycota. Zhao et al. [46] reported that as the soil's physical and chemical parameters, such as nutrient content, bulk density, and pH, changed, so did the relative abundances of Ascomycota and Basidiomycota. Ascomycota is very sensitive to labile C substrates and has a limited ability to breakdown resistant C. Ascomycota had substantial associations with labile C and N, such as MBC, DOC, and Nmin, implying that Ascomycota is engaged in the mineralization of organic matter. Furthermore, the soil enzyme activity in the MRI treatment were the highest. The MmRi treatment boosted soil urease activity by 33.5 percent, cellulase activity by 37.2 percent, invertase activity by 12.6%, and phosphatase activity by 8.9% when compared to CK (Fig. 8b). Although soil enzyme activities were lower under MiRi treatment than under MmRi treatment, the MiRi treatment considerably increased soil urease activity by 22.0 %, cellulase activity by 21.9 %, and invertase activity by 6.8% when compared to CK.

Soil microbes primarily degraded straw. This technique is thought to be divided into two phases. Because bacteria grow faster and are thought to be less capable of digesting refractory substances than fungus, bacteria dominate the first phase while fungus dominate the second [47]. Fungal diversity, on the other hand, responded just as quickly as bacterial diversity, suggesting that bacteria and fungi may also play

essential roles in the early stages [48]. With straw return treatment, the structures of soil microbial communities alter as well. According to Yu et al. [49], 99.11 percent of the sequences belonged to the Bacteria domain, whereas 0.89 percent belonged to the Archaea domain. There were also 39 phyla, 75 classes, 160 orders, 277 families, and 460 genera identified. Proteobacteria was the most common phylum, accounting for 92.4 % to 94.4 % of all sequences, followed by Acidobacteria, Firmicutes, Actinobacteria, Gemmatimonadetes, Bacteroidetes, Nitrospirae, Chloroflexi, Planctomycetes, and Verrucomicrobia. Despite the fact that there were no significant differences in relative abundance of these ten phyla between straw return and removal treated soils at both depths, fluctuations in the abundance of Proteobacteria and Chloroflexi between the two soil depths under straw return treatment were different from those under straw removal, indicating that straw return altered their vertical distributions (Fig.9). Proteobacteria and Chloroflexi were shown to be more susceptible to straw return treatment than other bacteria groups.

According to Banerjee et al. [36], fertiliser and organic amendments have a substantial impact on MBC in wheat (Fig. 10a). The FYM treatment (185 mg kg^{-1}) in the no-tilled plot had the highest MBC value, followed by the green manure treatment (183 mg kg^{-1}) in the tilled plot. In comparison to the control, plots receiving agricultural leftovers exhibited a considerable increase in soil MBC. In tilled soil, the maximum MBC (178 mg kg^{-1}) was found in the FYM treatment, while in 100 percent organic source treated no-tilled soil, the value was 176 mg kg^{-1} (Fig.10a). In rice-wheat systems, the trends in MBC content in the soil differed between two types of rice establishment: puddled and non-puddled direct-seeded. The MBC remained unaltered during the two-year cropping period in the case of puddled, transplanted rice followed by either tilled or no-tilled wheat (Fig.10a). However, there was an increase in MBC when non-puddled, direct-seeded rice was followed by either tilled or no-tilled wheat (Fig. 10b). Though MBC in the direct seeded rice-wheat system was initially lower than in the transplanted rice-wheat system, after two years of cropping, MBC was comparable. This revealed that puddled rice had an instant advantage in terms of greater MBC, whereas non-puddled rice had a lag phase of up to 2 years to build up microbial biomass.

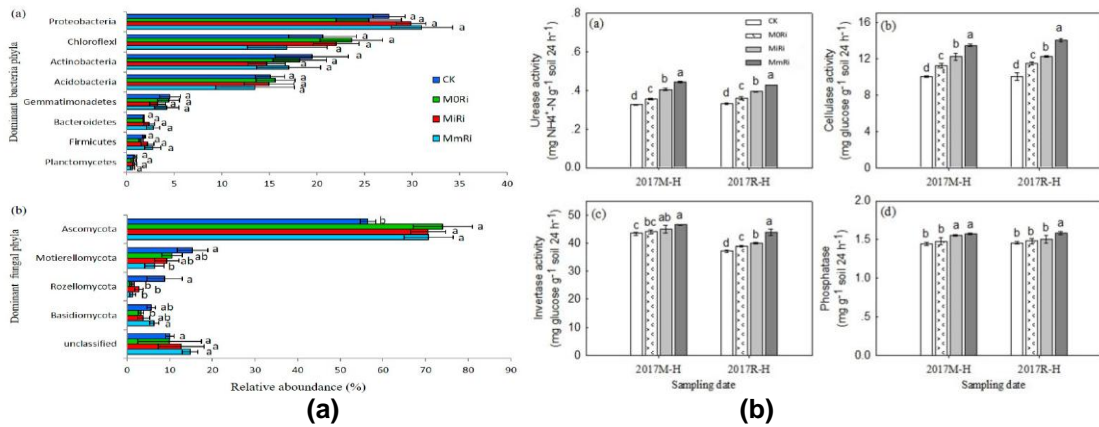(a)   (b)

Fig. 8a. Relative abundance of the dominant bacterial and fungal phyla in different straw-return treatments. (a) Relative abundance of the dominant bacteria phyla in different straw-return treatments. (b) Relative abundance of the fungal phyla in different straw-return treatments
Fig. 8b Changes in (a) soil urease, (b) soil cellulase, (c) soil invertase, and (d) soil phosphatase activities in the 0–20 cm soil layer under different treatments
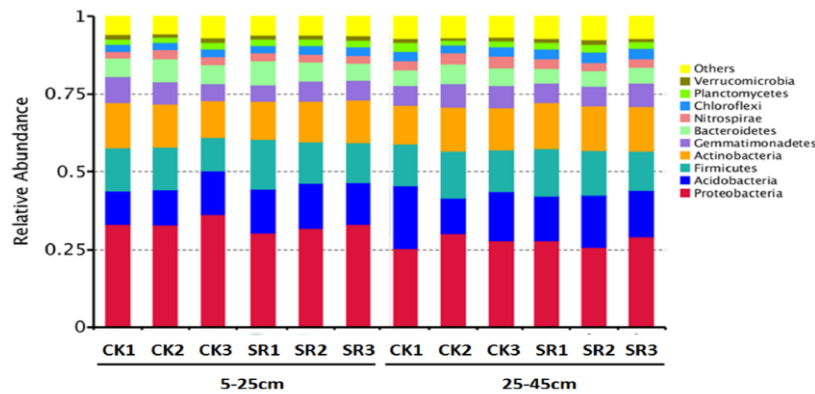

Fig. 9. The relative abundance of the 10 most prevalent bacterial phyla in soil samples after various treatments

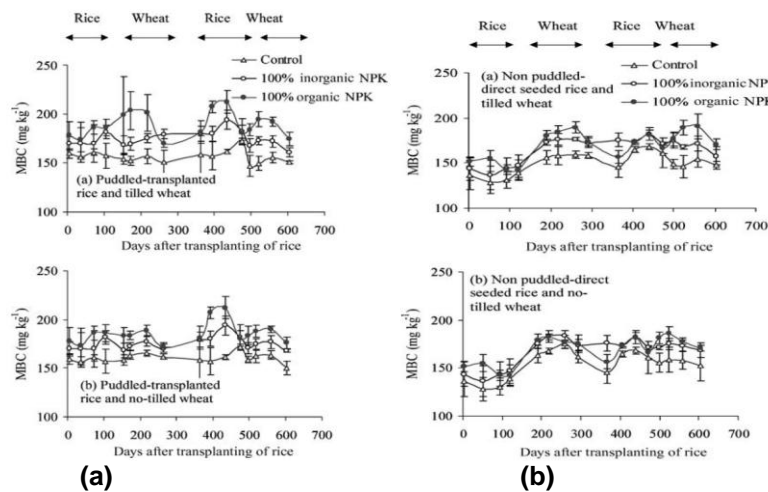(a)   (b)

Fig. 10a. Microbial biomass carbon (MBC) content of the soil in (a) puddled-transplanted rice and tilled wheat and (b) puddle-transplanted rice and no-tilled wheat
Fig. 10b. Microbial biomass carbon (MBC) content of the soil in (a) non-puddled direct-seeded rice and tilled wheat and (b) non-puddled direct-seeded rice and no-tilled wheat

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According to Jia et al. [50], the OM treatment considerably increased soil organic carbon (SOC), water-soluble carbon (WSC), total nitrogen, microbial biomass carbon and nitrogen (MBC and MBN), and dramatically decreased MBC: MBN ratios as compared to the NF treatment [Fig.11a]. Organic fertilisers also provide a consistent source of organic carbon and nitrogen for soil microbial growth, resulting in higher MBC and MBN [51]. Niu et al. [52] found that the biological crusts have higher microbial biomass carbon and content than the physical crust. With depth, all of the microbial biomass carbon concentrations of the five crust and strata samples decreased. At the same depth, the moss crust (crust 3) and underlying soil layers had larger microbial biomass carbon levels than the algal crust and underlying soil layers [Fig.11b].

According to Jiang et al. [53], bacterial biomass C varied from 106 to 464 mg C kg^{-1} soil and fluctuated with aggregate size, but was highest for 1– 2mm and 0.053–0.25mm aggregates (Fig.12a). Bacterial biomass was 52 percent and 73 percent greater in the total soil under NT than CT and FPF, respectively. Bacterial biomass fluctuated in a way that corresponded to various aggregate sizes. For all tillage regimes, the maximum bacterial biomass was found in the 2.0–1.0 mm and 0.25–0.053 mm fractions. In macro-aggregates >1.0mm, few tillage impacts were found, with CT supporting the maximum bacterial biomass in aggregates >4.76 mm. Tillage impacts, on the other hand, were particularly noticeable in aggregates smaller than 1.0 mm. NT had the highest bacterial biomass under 1mm, while FPF had the lowest. For aggregates less than 1.0 mm, bacterial biomass was 54 percent greater in NT than in CT, and 104 percent higher in FPF (Fig. 12a). Fungal biomass was 43 percent and 84 percent higher in the whole soil under NT than under CT and FPF, respectively. Fungal biomass ranged from 81 to 736 mg Ckg^{-1} soil, with macro-aggregates >1.0mm (445, 624, and 424 mg Ckg^{-1} soil for CT, NT, and FPF, respectively) having considerably greater biomass than the three micro-fractions 1.0mm (109, 230, and 108 mg C kg^{-1} soil for CT, NT, and FPF, respectively). Regardless of tillage regime, the average fungal biomass for macro-aggregates >1mm (498 mg C kg^{-1} soil) was 3.3 times higher than for micro-fractions 1mm (149 mg C kg^{-1} soil). For all tillage regimes, fungal biomass grew significantly from >4.76mm to the 2.0–4.76 mm fractions, then dropped with decreasing aggregate size until the 0.25–1.0 mm

fraction. Then, in fractions less than 0.25 mm, fungal biomass remained unaltered. Fungal biomass was higher for NT than other tillage regimes for all aggregate size fractions except 0.053mm. The availability of substrate and pore-size distribution are thought to be connected to qualitative changes in microbial communities between micro-aggregates and macro-aggregates (Fig.12b).

5. STRAW RETURNING ON CARBON MINERALIZATION

In soil science, mineralization is the decomposition (i.e., oxidation) of chemical compounds in organic matter, resulting in the release of nutrients in soluble inorganic forms that may be available to plants [54]. Immobilization is the polar opposite of mineralization. Mineralization enhances the bioavailability of nutrients found in degrading organic materials, particularly nitrogen, phosphorus, and sulphur, which are abundant. The proportion of an organic compound's concentration to the carbon in the organic matter determines whether it will mineralize or immobilize during decomposition. Mineralization occurs when the concentration of a specific element exceeds the decomposer's requirement for biosynthesis or storage. Understanding the mechanisms for soil carbon storage and stability in relation to land management is becoming increasingly important, as soil organic carbon (SOC) is recognized as a key source of global C and is essential for soil productivity. Physical protection of SOC within stable soil aggregates is thought to be one of the most important mechanisms for SOC stabilization.

The rates of C sequestration were estimated using the temporal trend in the recent SOC pool (0–40 cm in NR (23.2 Mg C ha^{-1}), 9-yr MP (32.9 Mg C ha^{-1}), and 13-yr MP (33 Mg C ha^{-1}), and ranged between 0.8 and 0.25 Mg C ha^{-1} yr^{-1} throughout the first and second decades of restoration, according to Jacinthe and Lal [55]. Despite the same quantity of crop residue returned (2.8 Mg C ha^{-1} yr^{-1}), recent SOC under 13-yr NT (36.8 Mg C ha^{-1}) was 3.8 Mg C ha^{-1} higher than that under 13-yr MP. According to Saswat [56], the condition of soil organic carbon decreased as soil depth increased. After the crop was harvested, the average SOC amount was determined to be 10.33, 8.73, 7.19, and 3.34 g kg^{-1} at soil depths of 0- 15 cm, 15-30 cm, 30-45 cm, and 45-60 cm. In the top layer, Treatment T5 had the greatest SOC of 11.80g kg^{-1}. Treatment

T5 had the largest SOC stock and SOC sequestration rate (46.29 t ha^{-1} and 4.00 t ha^{-1} year^{-1}). The contribution of soil layers to TPM varied among aggregate size classes, according to Khan et al. [57]. The standardised coefficient of the 20–30 cm soil layer was 0.47 for LM>2, which was greater than the 0–5, 5–10, and 10–20 cm layers. As aggregate size classes shrank, the contribution of the surface layer to total C mineralization in the 0–30 cm layers rose. NTS against RTS, CTS, and CT decreased TPM in the surface 30 cm layer across all aggregate size classes, owing to the lower contribution of macro-aggregates. NTS versus RTS, CTS, and CT decreased TPM in the surface 30 cm layer across all aggregate size classes.
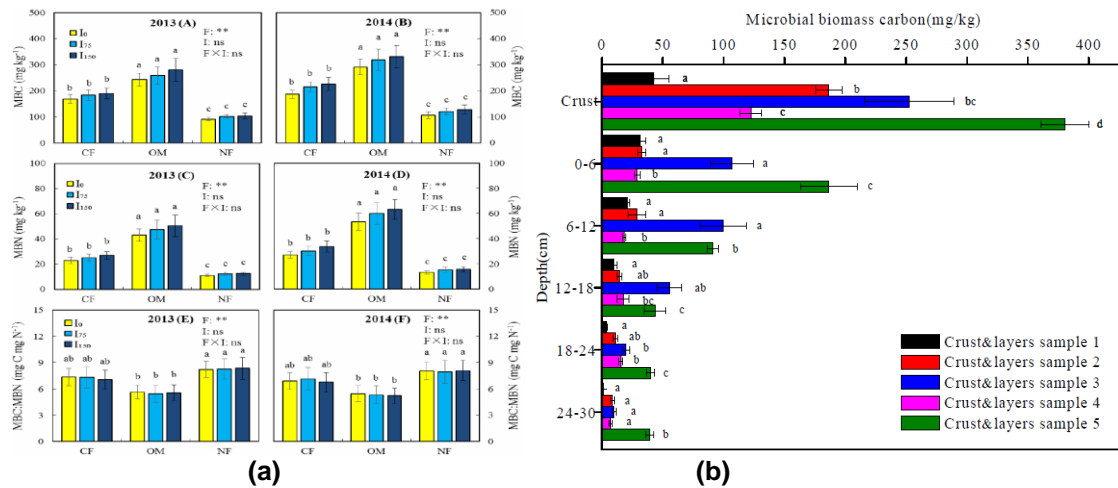

Fig. 11a. Effects of different treatments on microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and the MBC: MBN ratio in 2013 and 2014. (A) Microbial biomass carbon in 2013. (B) Microbial biomass carbon in 2014. (C) Microbial biomass nitrogen in 2013. (D) Microbial biomass nitrogen in 2014. (E) MBC: MBN ratio in 2013. (F) MBC: MBN ratio in 2014. Note: CF, Chemical fertilizer; OM, Organic manure and chemical fertilizer; NF, No fertilizer; I$_0$: 0 mm irrigation; I$_{75}$, 75 mm irrigation; I$_{150}$, 150 mm irrigation. F, fertilization; I, Irrigation; ns, not significant

Fig. 11b. The microbial biomass carbon contents of the five crust and layers samples at different depths
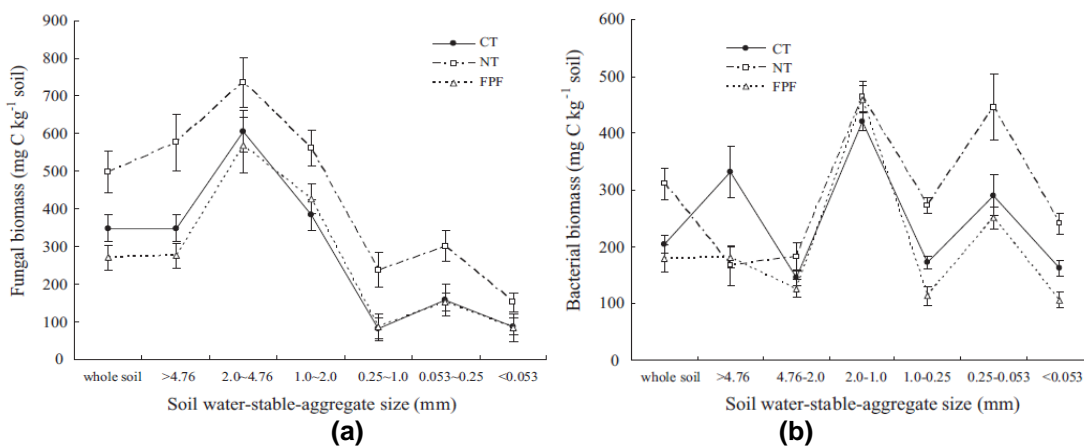

Fig. 12a. Distribution of fungal biomass within soil aggregates under different tillage management (CT, conventional tillage; NT, combines ridge with no-tillage; FPF, flooded paddy field)

Fig. 12b. Distribution of bacterial biomass within soil aggregates under different tillage management (CT, conventional tillage; NT, combines ridge with no-tillage; FPF, flooded paddy field)

The maximum SOC content (0.87 percent) was discovered in a combination of minimum tillage (MT) with tree crop residues retention (rice, wheat, and mung bean), while the lowest 0.44 percent SOC content was observed in a combined treatment of (deep tillage) DT with no crop residues retention. The slow breakdown of a large amount of residue kept on soil under MT could lead to increases in SOC [58]. When compared to the other treatments, Kumar et al. [59] observed that the ZTR (zero till with residue retention) (T1) and RTR (Reduced till with residue retention) (T3) had considerably greater BC, WSOC, SOC, and OC content of 24.5 percent, 21.9 percent, 19.37, and 18.34 kg^{-1}, respectively. Regardless of residue retention, wheat grown in zero-till plots increased BC, WSOC, SOC, and OC in surface soil by 22.7 %, 15.7 %, 36.9%, and 28.8%, respectively, when compared to conventional tillage. Simultaneously, residue retention in zero tillage increased BC, WSOC, SOC, and OC by 22.3 percent, 14.0 percent, 24.1 percent, and 19.4 percent, respectively, compared to no residue management treatments. Under subsurface (15–30 cm) soil, similar increasing trends of conservation methods on different kinds of carbon were detected, but the amplitude was significantly lower.

After two years of rice-wheat rotations, Hu et al. [60] found that wheat straw returning treatments, compared to CK, increased SOC stock, with WD increasing SOC stock by 12.9 percent. WR had no significant effect on SOC stock, however SOC stock was 1.86 times that of CK, whereas WP had no effect on SOC stock when compared to CK. The effects of three wheat straw returning treatments on SOC sequestration were distinct. Under WP, SOC sequestration was almost nil (Fig. 13b). When compared to WP, WD increased SOC sequestration by 4.0 percent. The difference in therapy between WR and WD was not significant (Fig. 13b). This might be linked to WP's enhanced soil disturbance and degradation of soil aggregate structure, which not only exacerbated soil loss but also accelerated soil C buildup and decomposition.

Regardless of the duration of the experiment, straw returning is an effective approach to raise SOC, and the rate of SOC sequestration has a substantial positive association with the amount of straw returning [61]. WD had considerably higher SOC sequestration than WP in this investigation. For instance, because wheat straw was compacted in anaerobic conditions during the rice season, less of it degraded, resulting in more leftover straw being continuously degraded in the next wheat season under WD. SOC sequestration may be increased if there is more remaining straw [62]. Second, bacteria degraded more C in WP, releasing CO_2 and CH_4 into the atmosphere [63], resulting in decreased SOC sequestration. Although there was no significant difference in SOC sequestration between WD and WR in our study, WD had higher SOC sequestration than WR.

Awanish [64] found that at the surface layer, there were more variances in carbon fractions (0-5 cm). F1 stands for very labile, F2 for labile, F3 for less labile, and F4 for non-labile. The C percent in vertisols varied in this order at this depth: F4>F1>F2=F3. The carbon fraction was in the following order below 5 cm: F4 >F1 >F3>F2. F4 >F1 >F2>F3 was the order for 15-30 cm depth. At lower depths, the pattern was virtually identical to that of 30-45 cm (Fig.14). At 0-5cm depth, the contribution of distinct carbon (C) fractions to the TOC varied from 33 to 41 percent; 9.30 to 30.11 percent; 8.11 to 26 percent; 30.6 to 45.20 percent for extremely labile, labile, less labile, and non-labile fractions, respectively, regardless of the tillage strategy. The contribution of different fractions to the TOC in the subsurface layer (5-15 cm) ranged from 27.8 to 40%; 7.80 to 12.40 %; 11.11 to 19.0 %; 38.0 to 50.0 % for extremely labile, labile, less labile, and non-labile fractions, respectively. The very labile fraction (F1), which contributed roughly 40% or more on the surface and surface layers (0–5 and 5–15 cm) compared to deeper layers (15–30 and 30–45 cm), declined with increasing depth. Furthermore, fewer labile and non-labile fractions contribute more than 50% of TOC, indicating that the soil's carbon is more resistant. Crop residues are progenitors of the SOC pool, according to Dolan et al. [65], and returning more crop residues to the soil leads to higher SOC concentrations. The volume and type of residues returned to the soil may influence the effects of conservation tillage on SOC buildup. Furthermore, tillage causes a redistribution of organic matter in the soil. The stability of macro-aggregates can be influenced by small changes in soil organic carbon.
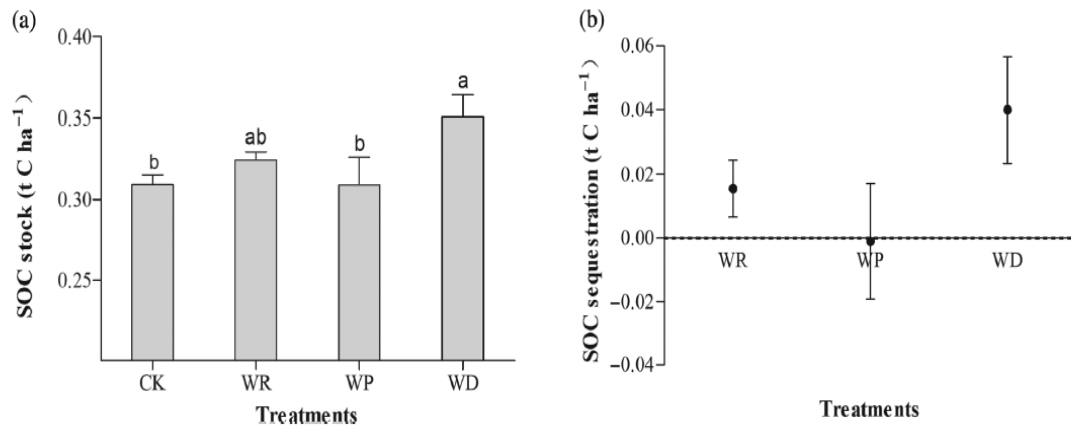
Fig. 13. Effects of different straw returning modes on soil organic carbon (SOC) stock (a) and sequestration (b)
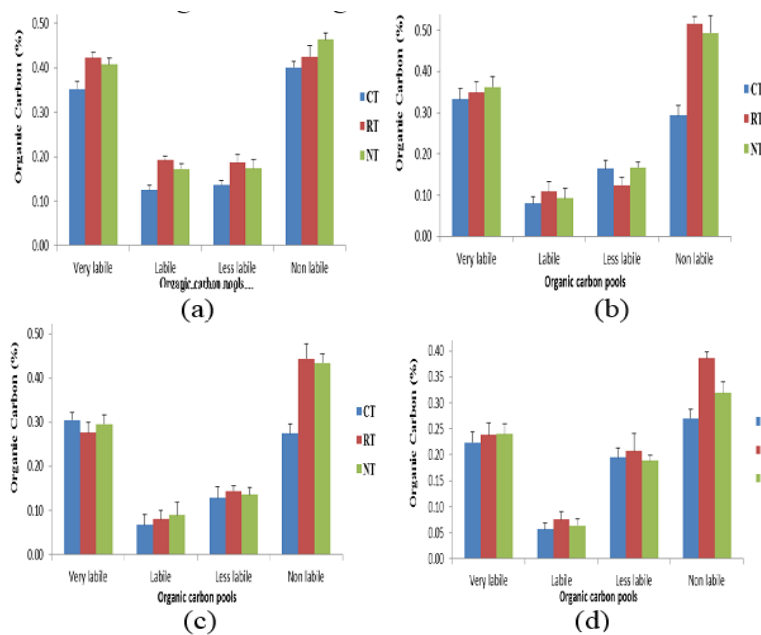

Fig. 14. Effect of conservation agriculture on organic carbon pools (%) in (a) 0-5 cm (b) 5-15 cm (c) 15-30 cm and (d) 30-45 cm depth under different tillage system

6. CONCLUSIONS

This review paper focused on a comprehensive evaluation of SOC and its fractions in various aggregate particle sizes in response to various tillage management techniques. Tillage had a greater impact on changes in SOC and labile carbon fractions content in large-size macro-aggregates than on SOC and labile carbon fractions distribution modes in soil aggregates, according to the findings. NT treatment increased not only the stability of soil aggregates, but also the content of SOC, DOC, and POC, particularly in large-size macro-aggregates, as compared to

RT treatment. Improvements in management practises may improve soil C sequestration capacity even more, and RR combined with a lower nitrogen fertiliser input rate (0–120 kg N ha-1), single cropping system, paddy-upland rotation, various RR procedures (including residue cutting, uniformly integrating, and burying), or long-term use (>10 years) is indicated to increase SOC store by 11.6–15.5 percent. When evaluating SOC responses to RR, the duration of the return, the NFIR, the amount of residue, and the initial SOC content should all be taken into consideration. In general, RR can be employed as a long-term efficient and climate-

smart management practise. In the 0–5 and 5–10 cm soil layers, SOC and soil labile organic C percentages were positively associated. In the 0–5 cm soil layer, the sensitivity of labile organic C fractions differed with different treatments.

Microbial biomass improved as a response of the NT, and this rise was proportional for both bacteria and fungus. Conventional tillage reduced fungal biomass in macro-aggregates, and greater microbial biomass C: N ratios were detected in CT than NT, indicating a potential N constraint in macro-aggregates generated by tillage. In CA practises, the concentration of POC, MBC, and HWC was higher in the topsoil (0-10cm) than in the subsoil (10-20cm). In the 2.0-mm fractions, organic carbon concentrations in CA were 14.0, 12.0, 14.4, and 24.1 percent higher than in CF, respectively. In the 0-40 cm soil layer, the contents of SOC,LOC, DOC, POC, and EOC were 14.73%, 16.5%, 22.5%, 41.5%, and 21%, respectively, while in the 0-100 cm soil layer, they were 17%, 14%, 19%, and 30%. These findings show that the MBC and MBC-derived C under the fine-sized residue treatment could become a significant source of stable SOC over time due to strong physical and chemical bonds to the mineral soil matrix.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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