



Aggregate Associated Carbon, Aggregation and Storage of Soil Organic Carbon Respond to Organic and Synthetic Fertilizers in Cereal Systems: A Review

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ABSTRACT

Soil organic carbon (SOC) and its labile fractions are strong determinants of soil chemical, physical, and biological properties and the recycling of crop residues is an important factor affecting soil organic matter levels and soil quality. This collected review literature specifically aims on soil fertility related to aggregate associated carbon, aggregate-size distribution, aggregation and storage of soil organic carbon trends and their respond towards organic and synthetic fertilizers and also understanding of the effects of diverse soil management regimes on SOC sequestration in cereal

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systems. Several studies results showed that, with the exception of unfertilized control (CK) and nitrogen fertilizer (N) treatment, the concentration of SOC in the soil layer 0-20 cm increased. The SOC concentration and storage to depths of 60 cm is significantly affected by long-term fertilization. SOC concentrations and stocks below 60 cm for all treatments were statistically insignificant. The degree of SOC was higher in farmyard manure plus N and P fertilizers (NP+FYM) at different depths, compared with CK, at 0-60 cm soil profile and followed by straw plus N and P fertilizers (NP+S) respectively. SOC storage in NP+FYM, NP+S, FYM and nitrogen and phosphorus (NP) fertilizers treatments increased by 41.3%, 32.9%, 28.1% and 17.9% respectively compared to CK treatment in 0–60 cm. Organic manure plus inorganic fertilizer application also increased organic carbon pools of the labile soil at depths of 0–60 cm. Particulate organic carbon (POC), dissolved organic carbon (DOC) and microbial biomass carbon (MBC) average concentration in organic manure plus inorganic fertilizer treatments (NP+S and NP+FYM) increased by 64.9–91.9 percent, 42.5–56.9 percent and 74.7–99.4 percent over CK treatment. The average control treatment SOC concentration was 0.54 percent, which increased to 0.65 percent in RDF treatment and 0.82 percent in RDF+FYM treatment and increased enzyme activity, potentially affecting soil nutrient dynamics in field conditions. The RDF+FYM treatment sequestered 0.28 Mg C ha⁻¹ yr⁻¹ compared with the control treatment while the NPK treatment sequestered 0.13 Mg C ha⁻¹ yr⁻¹ respectively. It can be concluded that long-term additions of organic manure have the most beneficial effects on the production of carbon pools, improve the availability of SOC and also enhance C sequestration in soils.

Keywords: Aggregate dynamics; Soil Organic Carbon (SOC); SOC fractions.

1. ROLE OF SOIL ORGANIC MATTER FOR MAINTAINING SUSTAINABILITY IN CEREAL SYSTEMS

Soil organic matter (SOM) plays a key role in enhancing physical, chemical and biological properties of soil [1]. Conserving the quantity and consistency of soil organic matter (SOM) is often seen as a central component of sustainable soil conservation and soil consistency maintenance [2]. Organic manure and inorganic fertilizer are the most common materials used to boost soil quality and crop productivity in agriculture management [3]. Numerous studies have shown that balanced application of inorganic fertilizers or organic manure plus inorganic fertilizers may increase SOC and maintain soil productivity [4, 5]. However, due to the high background levels and natural soil variability, SOM is not immune to short-term changes in soil quality with specific soil or crop management practices [6]. Labile soil organic carbon pools such as dissolved organic C (DOC), microbial biomass C (MBC), and organic particulate matter C (POC) are the fine soil quality indicators that affect soil function in different ways (e.g., immobilization – mineralization) and are much more prone to changes in soil management practices [7,8]. Since these components can react quickly to changes in supply of C, early indications of the effects of land use on quality of SOM have been suggested [9].

Adoption of agronomic measures such as proper tillage operations, the use of such kind of crop rotations that can improve soil organic matter and similarly the application of organic fertilizers, i.e., FYM, compost, green manuring, cover crops and other organic amendments such as humic acid, vermicompost, etc., can be useful in soil carbon sequestration and also improve organic carbon in soil, soil aggregation, water holding capacity and soil productivity [10]. The combined use of organic and inorganic fertilizers will increase soil nutrient content as well as the highest productivity contribution to soil fertility. The use of organic manure alongside inorganic fertilizers also contributes to an improvement in soil organic matter (SOM), soil structure, water holding capacity and increased nutrient cycling and helps to maintain soil nutrient status, cation exchange capacity (CEC) and soil biological activity [11]. Integrated soil fertility management involving the prudent use of combinations of organic and inorganic resources is a feasible approach to overcoming soil fertility constraints and contributing to high crop productivity in cereal systems [12].

A number of studies on cropping systems have shown that long-term application of chemical fertilizers increases the amount of macro-aggregates [13]. Although, other studies reported that application of chemical fertilizers does not significantly affect the amount of macro-

aggregates [14]. Organic manure application generally promotes macro-aggregate formation [15], but may not exert such effect in some instances [16]. In addition, long-term application of chemical fertilizers with or without manure increases SOC contents in macro-aggregates [14,17] and micro-aggregates [18,19]. Although, other studies reported neutral or opposite results [20,21]. These contradicting findings could be related to variations in fertilizer doses, fertilizer history, cropping system, soil type, soil properties, and climate conditions employed in the studies. This review study specifically aims to determine the effects of organic and synthetic fertilization regimes of cereal system on (1) aggregate-size distribution and stability, (2) sequestration of soil organic carbon in aggregates and (3) understanding of the effects of diverse soil management regimes on SOC sequestration particularly in Semi-arid Northwest India.

2. AGGREGATE-SIZE DISTRIBUTION AND TOTAL ORGANIC CARBON

Soil organic carbon is key attribute of soil fertility and productivity because of its influence on the physical, chemical and biological properties of soils [1]. Irrespective of its potential benefits to productivity and profitability, organic carbon might be sequestered by vegetation and soils as a possible way of reducing the rate of CO₂ enrichment of atmosphere and moderate the global climate change. Net change in SOC depends not only on the current management practices but also on the management history of the soil [22]. The existence of a positive difference between organic and non-organic systems in SOC amounts, stocks and C sequestration levels does not disclose whether this transition goes hand in hand with a net carbon gain due to conversion from traditional to organic farming or whether it represents a reduced carbon loss relative to non-organic treatment [23].

Singh et al. [24] have shown that addition of various organic manures along with inorganic fertilizers in rice-wheat system improved the aggregation status of the soil. Aggregate ratio varied significantly with treatments. Treatments where more organic matter was added through either FYM, CR and GM maintained a larger macro-aggregate fraction compared to the control. Sodhi et al. [25], a 10-year application of rice straw compost, either alone or in

combination with inorganic fertilizers, results in C sequestration in macro-aggregates. In fact, with the application of 8 t compost ha⁻¹, the C concentration in the 1–2 mm size fraction increased by 180 to 191%, respectively, over unfertilized control.

Zhou et al. [26] reported that the application of NPK plus OM increased the size of sub-aggregates that comprised the macro-aggregates. The cereal cropping system was continuous corn (spring corn–autumn corn) production in ultisols. Agronomic practices like moldboard plow tillage was implemented to about 20 cm depth before and after the autumn corn season and manual hoeing was used to prepare the seedbed. They also observed that long-term application of NPK plus OM improves soil aggregation and alters macro-aggregate tridimensional microstructure, while NPK alone does not. Land use change usually alters land cover and the terrestrial change in carbon stocks. Bappa Das et al. [27] revealed that the increased amounts of large (>2 mm) macro-aggregate fractions in NPK + GR (rice) + FYM (wheat) and NPK + CR (rice and wheat) are associated with the very large MWD in these treatments. Similar patterns are found in other organic treatments, with large amounts of small fractions of macro-aggregates along with large macro-aggregates. The control observed a higher amount of silt- and clay-sized fractions (43.84 per cent) in sandy loam soil. In the GR treatments, summer green gram was sown immediately after wheat harvest, and the above ground biomass was incorporated by dry tillage prior to puddling after pod picking. Both crops were grown using approved agronomic practices under assured irrigated conditions.

Bandyopadhyay et al. [18] observed in rice – wheat cropping system that long term application of NPK only resulted in a decrease in micro-aggregates, maintaining a similar MWD as compared with control treatment at a soil depth of 0–15 cm, but that it had no effects at 15–30 and 30–45 cm depths in an Inceptisol. On a sandy loam with an initial SOC content of 4.8 g kg⁻¹, increases in soil aggregation were observed after 7 years of incorporation of rice straw. Application of organics (FYM, PS and GM) along with inorganic fertilizer (NPK) in the rice–wheat system significantly improved aggregate stability, limiting the negative effect of ploughing but not to the level of native vegetation [28]. Fang et al. [29] indicated in typical red soil that the mass of soil aggregates of >5 mm diameter

was the greatest followed by 2–5 mm, 0.5–1 mm, 0.25–0.5 mm, and <0.25 mm and that of 1–2 mm aggregates was the lowest. Moreover, smaller aggregates had a higher OC concentration (0.5–1 mm, 0.25–0.5 mm and <0.25 mm) than larger aggregates (>5 mm, 2–5 mm and 1–2 mm) in CF topsoil, and OC concentration decreased with increasing aggregate size in BF topsoil. Although, the OC concentration varied very little between aggregate size classes at deep soil. Fang et al. [29] also found that the mass of soil aggregates of >5 mm diameter was the greatest followed by 2–5 mm, 0.5–1mm, 0.25–0.5 mm, and <0.25 mm, and that of 1–2 mm aggregates was the lowest. Moreover, smaller aggregates had a higher OC concentration (0.5–1 mm, 0.25–0.5 mm and <0.25 mm) than larger aggregates (>5 mm, 2–5 mm and 1–2 mm) in CF topsoil, and OC concentration decreased with increasing aggregate size in BF topsoil. Although, the OC concentration varied very little between aggregate size classes at deep soil.

Yan et al. [30] observed in maize - wheat system that particulate organic C was found stratified along the soil depth in dark loessial soil. A higher POC was observed diminishing with depth in surface soil. POC content under NP+FYM, NP+S, and FYM at 0–20 cm was 103, 89 and 90 per cent higher than under CK, respectively. NP+FYM had average POC in 20–40 cm and 40–60 cm soil layers which was considerably higher than NP+S and FYM treatments. Although POC below 60 cm depth was statistically similar among fertilization treatments, there was a general trend towards increased POC with manure from the farmyard or straw application down to 100 cm depth. Awanish, [31] reported 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. C fraction in vertisols at that depth 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 in Maize and wheat system.

Song et al. [32] recorded an increase of 17.22% and 36.38% in the 0–15 cm soil layer and 28.93% and 66.34% in the 15–30 cm soil layer compared with traditional tillage, In percentages of macro-aggregates > 2 mm and water-stable macro-aggregates in double-conservation rice-wheat tillage (zero-tillage and straw

incorporation) in water logged paddy soil. The highest proportion of total aggregated carbon was held in surface soil (0–15 cm), with aggregates of 0.25–0.106 mm, and the double-conservation tillage of rice-wheat had the greatest capacity to preserve organic carbon (33.64 g kg⁻¹).

3. SOIL ORGANIC CARBON (SOC) TRENDS

Manjaiah and Singh [33] also found that inorganic fertilizers plus organic material increased the SOC content of the soil. The causes for the higher SOC at deeper depths in manure soils include the following. Second, the extent of the rooting of crops varies between organic manure and inorganic fertilizer soils. Because of the relatively loose soil and high soil water content, organic manure soils can be beneficial for the root growth into deeper layers. Second, SOC in organic manure soils can also move to lower depths through earthworm burrows and leaching [34].

Gami et al. [35] reported that a significant increase in SOC stocks to 60 cm depth fewer than three 23–25-year-old long-term fertility experiments in the Nepal, with application of manure and inorganic fertilizer. Within 1 m soil depth, the cumulative distribution of SOC in the CK, N, NP, FYM, NP+S and NP+FYM treatments were by 50%, 46%, 51%, 53%, 54% and 55%, in the layer of 0–40 cm and 68%, 68%, 71%, 72%, 73% and 74%, respectively, in the layer of 0–60 cm. The soil C concentration level at 60 cm depth was on average 267 percent and 41 percent higher than that recorded at 20 cm depth and 40 cm depth for soil C, respectively. These findings suggest that the soil C accumulation estimate at a depth of 60 cm was more effective than that accumulated at 40 cm for soil C. In this research study, C input has been increased as opposed to CK under the N treatment. Under the N treatment, however, neither the concentration of SOC nor the storage of C had changed significantly. The explanation for this is that the treatment with N may stimulate microbial activity in the soil, thereby increasing the output of C. The increase in C mineralization might offset the increase in C input.

In terms of sustainability, only farmyard manure fertilization maintained the total organic carbon level of 40 t C ha⁻¹, measured in the top soil layers at the start of a 40-year experiment, while the average total organic C depletion was 23%

with liquid manure and mixed fertilization treatments, 43% with mineral fertilizers alone and 51% in the control [36]. Habteselassie et al. [37] found that, over a 5-year period, the C pool was enhanced by 115% in dairy-waste compost treated soil. Moreover, the dairy-waste compost increased organic carbon by 143 and 54% as compared with ammonium sulfate and liquid dairy-waste treatments, respectively, applied at the same available N level (200 kg N ha^{-1}). This C accumulated in the organic matter of the soil accounts for around 11 per cent of the total volume of C added. Application of farmyard manure at 20 t ha^{-1} in a rice – wheat system revealed, after 32 years, a 17 percent higher organic carbon concentration compared to NPK fertilizers in the 0–15 cm soil layer [38].

Pathak et al. [39] revealed that compared to the NPK treatment also, the NPK+FYM treatment had higher SOC concentration in all the LTEs. The highest increase in SOC in the NPK+FYM treatment was observed in LTE 14 in New Delhi. Organic sources of nutrient such as FYM decompose slowly resulting in more SOC accumulation in soil [40]. Carbon sequestration in CSP NPK scenario denoted that even without any organic matter application soils could sequester organic carbon through balanced application of NPK. But application of FYM along with inorganic fertilizer led to an additional build up of SOC in soil. Average rate of sequestration was $0.33 \text{ MgC ha}^{-1} \text{ yr}^{-1}$ in the NPK+FYM treatment whereas in the NPK treatment the rate was $0.16 \text{ MgC ha}^{-1} \text{ yr}^{-1}$. The C sequestration rate was lowest in LTE 18 in the NPK treatment ($0.02 \text{ MgC ha}^{-1} \text{ yr}^{-1}$) whereas it was highest in LTE 25 ($1.2 \text{ MgC ha}^{-1} \text{ yr}^{-1}$) in the NPK+FYM treatment. The average C sequestration rate in the INM scenario, i.e., NPK+FYM treatment compared to NPK treatment, was 0.17 percent. Majumder et al. [41] indicated that application of NPK and organic amendments (FYM, straw, and green manure) could increase SOC by 24%. Jha et al. [42] also found that an application of bio-nutrient containing *Pseudomonas* mycostraw, *cyanobacteria* and *Azospirillum* increased SOC by 14 to 18% in a rice field in Bihar, India.

Hu et al. [43] reported that the straw mulching decreased soil carbon emissions by 16%, in comparison to treatments without mulch. However, topsoil organic carbon (C) increased by 0.9 ($0.7\text{--}1.0$, 95% confidence interval (CI)) g kg^{-1} (10.0%, relative change, hereafter the same), 1.7 ($1.2\text{--}2.3$) g kg^{-1} (15.4%), 2.0 (1.9--

2.2) g kg^{-1} (19.5%) and 3.5 ($3.2\text{--}3.8$) g kg^{-1} (36.2%) under unbalanced application of chemical fertilizers (UCF), balanced application of chemical fertilizers (CF), chemical fertilizers with straw application (CFS), and chemical fertilizers with manure application (CFM), respectively. Joshi et al. [44] observed that the SOC concentrations in the 0–20 cm soil layer for CK, N, NP, FYM, NP+S and NP+FYM treatments at the beginning of the study were 5.97, 6.15, 5.92, 6.38, 6.09, 6.03 g kg^{-1} . Although significant variations in SOC content have occurred over time, the SOC content in CK and N treatments has generally increased marginally over time and in NP. The concentration of SOC in the C input treatments (FYM, NP+S, and NP+FYM) increased significantly with the lapse of year. Over the 30 cropping and fertilization cycles, annual SOC concentration levels implied that in NP+S, FYM and NP+FYM treatments, 0.15 , 0.16 and $0.19 \text{ g kg}^{-1} \text{ yr}^{-1}$ were increased each year.

Ghosh et al. [45] observed that the plots with 50% NPK+ 50% FYM had significantly higher SOC content followed by 50% NPK + 50% GM in topsoil. Significantly lower bulk SOC was found with control plots in topsoil. Significantly higher (+35 and 38%) SOC with 50% NPK +50% FYM compared to control in both soil layers, respectively. Similar trend of bulk SOC was observed in the 5–15 cm soil layer. This increase was found due to significantly increased C input with organic amendments coupled with mineral fertilization. Build-up of organic carbon is more in surface layer than in lower depth because of more addition of roots and plant biomass in surface layers and lack of nutrient and biological activity in deeper layers, which ultimately constrain the rooting depth.

Brar et al. [46] revealed that better crop yields of maize and wheat with balanced application of organic manure and inorganic fertilizers may be attributed to improvements in soil physical properties along with sufficient supply of nutrients from FYM and inorganic fertilizers. The improved SOC concentration continuously from the initial level of 2.03 g kg^{-1} to 5.20 g kg^{-1} with application of FYM over 36 years might have also responsible for higher yields in treatments receiving FYM. Integrated use of inorganic fertilizer along with organic fertilizer (100% NPK + FYM) had resulted in maximum infiltration rate, cumulative infiltration, aggregate MWD, improved soil physical conditions and increase in SOC might have resulted in higher maize and

wheat yields. He concluded that balanced application of NPK fertilizers with FYM was best option for higher crop yields in maize-wheat rotation.

Zhao et al. [47] conducted a field experiment in a well-drained field Vertisol soil following 4-year compost and inorganic fertilizer amendments, i.e. no fertilizer (CK), mineral fertilizer (FR) and 60% compost N plus 40% fertilizer N (FRM) in wheat-maize system. He reported that the organic C content in all FR and FRM treatments was 8.24–41.15% higher than that in CK. An increased amounts of carbon cycle enzymes in aggregates or 0–20 cm bulk soil were also observed in FRM plots. Compared to FR, FRM significantly strengthened the structural stability of macroaggregates and the intimate connection between enzyme activities and macroaggregates. He concluded that, supplementation with organic manure such as compost strengthened the process of mutual promotion between carbon cycle enzymes and macroaggregates, and the synergistic effect would be highly beneficial to soil organic C sequestration.

4. SIZE DISTRIBUTION OF WATER-STABLE AGGREGATE

Soil water-stable aggregation is an important process for carbon sequestration and is a key factor controlling soil sustainability and resilience [48]. Water-stable aggregates were separated using an instrument similar in principle to the Yoder wet-sieving apparatus. The apparatus was modified and designed to handle three stacked sieves and to allow for complete recovery of all particle fractions from individual samples. Two hundred and fifty gram samples of soil were air-dried for 24 h and evenly distributed over the nested sieve surfaces. The nest was set at the highest point when the oscillation cylinders were filled with distilled water. Soil samples were completely covered with water. To slake the air-dried soil, 1 L of distilled water was rapidly added to each cylinder until the soil sample and top screen were covered with water. The soils were submerged in water for 10 min before the start of the wet-sieving action. The apparatus specifications of oscillation time (10 min), stroke length (4 cm vertical) and frequency (30 cycle min^{-1}) were held constant. Material remaining on each sieve was collected, dried at 60°C and weighed. The water-stable aggregate distribution was based on the percent of total mass in each aggregate fraction [49]. Material remaining on the

sieve after 5 min was oven dried (105°C) and weighed to give a "stable aggregate mass" (SA). After weighing, this material was dispersed by sonication in 60 mL of distilled water three times for 10 min each, and wet sieved for 5 min. The fraction remaining on the 0.25 mm sieve was oven dried and weighed to obtain the mass of X). 25 mm sand (SM) [50]. All soil samples of aggregates with different sizes were passed through a 0.15-mm sieve to determine SOC and total nitrogen (TN) contents. SOC was determined by potassium dichromate ($\text{K}_2\text{Cr}_2\text{O}_7$) oxidation at 170–180°C, followed by titration with 0.1 mol L^{-1} ferrous sulfate [51].

The WSA percentage was calculated by $\% \text{WSA} = [(S A - SM)/(\text{soil original mass} - SM)] \times 10$

Xie et al. [48] reported that generally, <0.25 mm aggregates accounted for the largest percentage, which ranged from 41 to 87%, whereas >2 and 1–2 mm aggregates showed the least percentage for most treatments at 0–10 and 10–20 cm two soil depths (Table 1). However, nutrient applications changed the distribution of >0.25 mm aggregates. Treatments of NK, NP, NPK, and MNPK showed significantly reduced percentages for >1 mm aggregates. The MNPK treatment exhibited significantly increased percentages of 0.25–1 mm soil aggregates at the 0–10 cm depth compared with CK (Table 1). Fertilizer treatments, except N, NK, and PK, decreased the percentages of >1 mm aggregates. The MNPK treatment showed significantly increased percentages for 0.25–0.5 mm soil aggregates at 10–20 cm soil depth compared with CK. The NPK treatment reduced the percentage of >0.25 mm soil aggregates and the corresponding MWD values at either soil horizons.

Different letters after the number inside each column suggest significant differences in and soil depth at $P < 0.05$ between treatments under the same soil management or wheat-fallow scheme. Much like the one below. The mean values of three replicates for all variables were compared using one-way ANOVA and separated using the LSD test at 95% confidence level.

Joshi et al. [44] revealed that the inclusion of manure increased responsive TOC fractions such as water soluble C, acid hydrolyzable carbohydrates, soil microbial carbon biomass (SMBC). However, in chemical fertilizer treatments the percentage increase was

Table 1. Distribution of water-stable aggregates (%) and mean weight diameter (MWD) [Source: Xie et al. [48]]

System	Treatment ¹⁾	Aggregate size (mm) ²⁾					MWD (mm)	
		>2	1-2	0.5-1	0.25-0.5	<0.25		
0-10 cm								
Soil management	Fallow	1.69 b	3.15 b	5.43 b	10.93 b	78.08 a	21.20 c	0.26 b
	Abandonment	33.69 a	10.25 a	10.12 a	4.93 c	41.01 c	58.99 a	0.97 a
	Cropping	3.41 b	5.27 b	12.29 a	16.06 a	62.97 b	37.03 b	0.38 b
Wheat-fallow	Ck	6.88 a	6.94 a	11.14 b	10.70 c	64.34 bc	35.66 ab	0.45 a
	N	5.45 ab	5.47 ab	12.57 b	14.76 bc	61.75 bc	38.25 ab	0.42 a
	NK	4.33 b	5.29 b	9.77 bc	12.92 bc	67.69 ab	32.31 bc	0.37 a
	PK	7.07 a	5.54 ab	9.76 bc	10.96 c	66.67 b	33.33 b	0.42 a
	NP	3.41 bc	5.27 b	12.29 b	16.06 ab	62.97 bc	37.03 ab	0.38 a
	NPK	1.82 c	2.98 c	7.98 c	11.88 bc	75.34 a	24.66 c	0.28 b
	MNPK	3.65 bc	4.45 bc	16.46 a	19.61 a	55.83 c	44.17 a	0.41 a
10-20 cm								
Soil management	Fallow	0.75 b	1.42 c	3.04 b	8.06 a	86.73 a	13.27 c	0.20 b
	Abandonment	20.40 a	11.05 a	8.66 a	5.56 b	54.33 c	45.67 a	0.73 a
	Cropping	3.19 b	3.63 b	8.28 a	9.87 a	75.03 b	24.97 b	0.31 b
Wheat-fallow	Ck	10.62 a	6.39 a	8.82 ab	7.62 c	66.55 b	33.45 a	0.49 a
	N	8.43 ab	6.11 a	7.21 b	7.68 c	70.57 ab	29.43 ab	0.43 ab
	NK	9.24 ab	5.82 ab	7.50 b	9.59 bc	67.85 b	32.15 a	0.45 ab
	PK	6.40 bc	5.47 abc	7.27 b	8.81 bc	72.05 ab	27.95 ab	0.39 ab
	NP	3.19 cd	3.63 bc	8.28 b	9.87 bc	75.03 ab	24.97 ab	0.31 b
	NPK	2.40 cd	3.14 c	5.99 b	11.36 ab	77.11 a	22.89 b	0.28 b
	MNPK	3.64 d	5.21 abc	11.76 a	13.46 a	65.93 b	34.07 a	0.37 ab

1) Fallow, bare fallow; abandonment, cropland abandonment; cropping, wheat-fallow cropping. CK: no nutrient input; N: nitrogen only; NK: nitrogen and potassium; PK: phosphorus and potassium; NP: nitrogen and phosphorus; NPK: nitrogen, phosphorus and potassium; MNPK: manure plus NPK. The same as below. 2) 0–10 and 10–20 cm, soil depths

comparatively lower compared to the combined fertilizer and manure application. The particulate organic matter carbon (POMC) appeared to be the most affected one. Higher content of POMC was noticed in macro-aggregates than micro-aggregates and declined substantially in the aggregates of 100% N- and 100% NP-treated plots leading to lower nutrient supplying capacity of the soils. Fractions of humic acid C, that is, a passive pool of TOC in combination with balanced fertilizer treatments was significantly higher in FYM in Vertisol under Rice-Wheat System.

5. DEPTH DISTRIBUTION OF SOIL ORGANIC CARBON

Li et al. [52] found that the surface layer, SOC and N_t concentrations appeared as a bimodal peak in the 250–2000 and $<2\mu$ m fractions. SOC concentration increased by 38.6, 40.8 and 17.2% and N_t concentration by 30.0, 16.8 and 38.4% in the 250–2000 μ m fractions under chemical fertilizers plus pig manure (CFM), chemical fertilizers with straw return (CFS) and chemical fertilizers (CF) respectively as compared with NF treatment in paddy soil (Ferric-accumulic Stagnic Anthrosols).

Mazumdar et al. [53] reported that organic C distribution in soil profile differed significantly among the treatments and with depths in rice-wheat cropping system. At the surface (0-15 cm) layer, NPK+FYM contained the highest SOC concentration (7.7 g kg^{-1}) followed by NPK+CR (7.5 g kg^{-1}) and NPK+GM (7.4 g kg^{-1}). There was a significant reduction in SOC concentration with the sole application of inorganic fertilizers (NPK) compared with those in the mixed organic and inorganic treatments. The lowest SOC concentration (3.6 g kg^{-1}) in 0-15cm layer was observed in treatment of a continuous cropping of rice-wheat over 25 years without any amendments. Mean SOC concentration in the profile increased from 2.4 g kg^{-1} in control to 4.1 g kg^{-1} in NPK+FYM. All the treatments showed higher accumulation of SOC in surface layer. Significant variations in SOC content were also observed in the sub-soil layers; mean SOC content decreased from 6.4 at surface 0-15 cm to 1.8 g kg^{-1} at 45-60 cm soil layer.

Song et al. [32] revealed that soil organic C content was highest in the topsoil (0–0.2 m), and then decreased rapidly with soil depth. In the topsoil layer, SOC content in MNPK, FAL and SNPK was significantly higher than that in the

unfertilized control by 50.7, 25.6 and 12.4%, respectively, whereas no significant difference was found between the unfertilized control and NPK. In the subsoil (0.2–0.4 m) layer, SOC contents in MNPK and FAL were significantly higher than for the unfertilized control, NPK and SNPK, but no significant differences were observed among the unfertilized control, NPK and SNPK treatments. In the 0.4–0.6 m and 0.6–0.8 m layers, MNPK had the highest SOC content among the treatments. The SOC concentrations in MNPK, FAL and SNPK treatments increased significantly by 61.0, 34.1 and 20.1%, respectively, compared to their initial level in the topsoil.

Mi et al. [54] revealed that the TOC and TN concentrations were both highest in the upper 0–5 cm depth and then decreased with increasing depth in paddy soil. However, addition of organic materials resulted in significant increases in TOC concentrations compared to the CK, ranging from 16.0–29.5% in the 0–5 cm depth, and 18.3–28.9% in the 5–10 cm depth, respectively. Generally, no significant differences in TOC concentrations were observed between treatments at the deeper soil depth (20–30 cm). All fertilized treatments showed significant increases in soil TN in the 0–20 cm soil layer compared to the control. In comparison with NPK alone, the TN concentration in the FM treatment was 19.1% higher in the 0–5 cm depth, and increased by 5.9%, 12.7% and 7.6% in the FG, FM and FS treatments in the 5–10 cm depth, respectively.

Joshi et al. [44] also found that the highest SOC concentration was obtained for 0–20 cm depth and decreased with depth for all treatments in vertisols of rice-wheat system. The concentration of SOC at depths of 0–20, 20–40 and 40–60 cm increased significantly through the application of manure or straw on the farmyard. At soil depths of 0–20 and 20–40 cm, SOC was the maximum in NP+FKM followed by treatments with NP+S and FYM and the least in treatment with CK.

6. SOIL ORGANIC CARBON STORAGE

Srinivasarao et al. [55] reported that the surface 0.2 m layer, 50 per cent RDN (F) + 50 per cent RDN (FYM) contained the highest SOC concentration (2.7 g kg^{-1}) followed by that in 50 per cent RDN (FYM) (2.2 g kg^{-1}) and 100 per cent RDN (F) (1.7 g kg^{-1}). There was a significant reduction in SOC concentration with the sole application of inorganic fertilizers (100 per cent

RDN) compared with those in the mixed organic and inorganic or sole FYM treatments in pearl millet- cluster and bean- castor rotation system. Srinivasarao et al. [56] also found that in comparison with the control,% increase in SOC stock was in the order 100% organic (FYM) treatment (55.0) > 50% organic (FYM)+50% RDF (35.2) > 100% RDF (mineral) (15.3).This trend was reflected in the profile SOC stock of the respective treatments. The mean rate of change in SOC stock followed a trend similar to that of SOC stock. The SOC stock declined in all but two treatments (100% FYM, 50% FYM + 50% RDF) in Rice–Lentil Cropping System. The mean rate of SOC sequestration in two treatments which enhanced SOC stock over 21 yr was 0.32 Mg ha⁻¹ yr⁻¹ for 100% FYM and 0.15 Mg ha⁻¹ yr⁻¹ for 50% FYM + 50% RDF. However, results showed that 13.4% C applied as FYM was stabilized in SOC stock. Nayak et al. [57] reported that an application of 50% NPK + 50% N through FYM in rice and 100% NPK in wheat, sequestered 0.39, 0.50, 0.51 and 0.62 Mg C ha⁻¹

yr⁻¹ about control (no N – P – K or organic fertilizers).

Xie et al. [48] also indicated that SOC storage in <0.25 mm aggregates was not affected by nutrient management at 0-10 and 10-20 cm soil layers, except for the NPK treatment at 0–10 cm depth, which yielded significantly higher value than that of CK (Fig.1). However, SOC storage in soil aggregates treated with NP, NPK and MNPK was lower in >1 mm aggregates compared with those treated with CK at both soil depths. Higher SOC partitioning proportions were also observed in 0.25–1 mm aggregates at 0–10 cm and 0.25–0.5 mm aggregates at 10–20 cm depth in soil treated with MNPK than those in CK (Fig. 1). Nevertheless, TN storage in <0.25 mm aggregates was less affected by nutrient management at both soil layers, except for the NPK treatment at 0–10 cm depth, which obtained a significantly higher value than that of CK (Fig. 2). The TN storage in soil aggregates treated with NP, NPK and MNPK showed lower

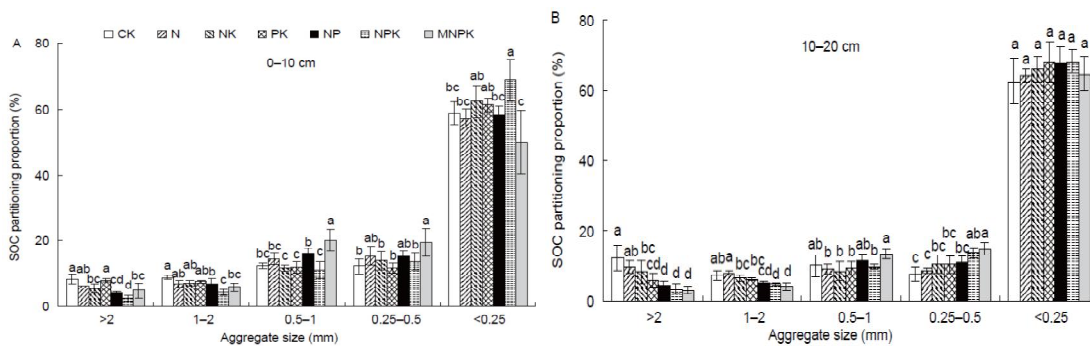


Fig. 1. Soil Organic Carbon (SOC) partitioning proportions (%) in water-stable aggregates in 0–10 cm (A) and 10–20 cm (B) soil horizons under different fertilizer treatments. CK, no nutrient input; N, nitrogen only; NK, nitrogen and potassium; PK, phosphorus and potassium; NP, nitrogen and phosphorus; NPK, nitrogen, phosphorus and potassium; MNPK, manure plus NPK

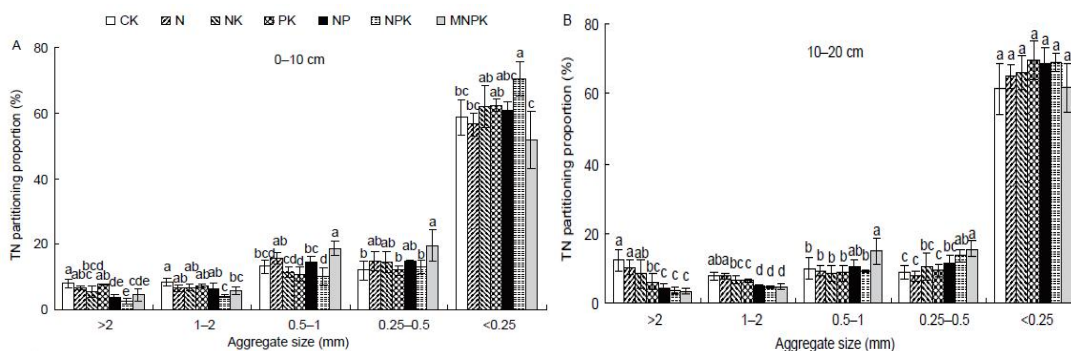


Fig. 2. Total nitrogen (TN) partitioning proportions (%) in water-stable aggregates in 0–10 cm (A) and 10–20 cm (B) soil horizons under different fertilizer treatments

proportions in >1 mm aggregates at both soil depths than that in aggregates treated CK, except for 1–2 mm aggregates under NP at 0–10 cm depth. However, TN storage showed consistently higher values in 0.25–1 mm aggregates at two soil depths under the MNPK treatment (Fig. 2).

Zhu et al. [58] also found that soil TOC and labile organic C fractions were substantially affected by straw returns, and higher than non-straw return at three depths under straw return treatments. At a depth of 0–7 cm, soil MBC under plowing tillage was substantially higher than rotary tillage, but EOC was just opposite. Rotary tillage had significantly higher soil TOC than tillage plowing at a depth of 7–14 cm. However, under plowing tillage, TOC, DOC and MBC were significantly higher than rotary tillage except for EOC, at 14–21 cm depth. The reason might be that rotary tillage and plowing tillage mixed crop straw into the deeper soil layer, making SOM well distributed at different depths. Consequently, both rice and wheat straw returns in the rice-wheat rotation system could increase the SOC content and improve soil quality under short-term conditions. Under Cropping, application of mineral fertilizers alone, especially balanced fertilization (NP or NPK), significantly increased SOC content in aggregates as a result of increased crop yield and SOC in bulk soil [59]. Yu et al. [14] who found that SOC concentrations in all fractions of aggregates increased after manure application for 16 years or compost incorporation for 18 years. The application of manure produces various organic carbon compounds from organic crop residues to humus, including the composition of all carbon fractions, thereby significantly increasing the root biomass and returning substantial quantities of carbon to the soil [60].

Joshi et al. [44] reported that in vertisols of rice-wheat system, 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. The SOC stocks of NP, FYM, NP+S and NP+FYM treatments were significantly higher in the 20–40 cm and 40–60 cm soil layers by 17%, 21%, 25 %, 37%, and 5.3%, 8.1%, 7.3% and 11%, respectively, compared to the CK. Differences in SOC storage in the 60–80 cm and 80–100 cm soil layers among different treatments were not important. SOC storages in the 0–100 cm range varied greatly between the

fertilization treatments. Compared to CK treatment, NP+FYM, NP+S, FYM and NP treatment storages were increased by approximately 30, 24, 20 and 12 percent, respectively, within the 0–100 cm soil depth. Krishna et al. [61] revealed that the total organic carbon (TOC) allocated into different pools in order of very labile > less labile > non labile >labile, constituting about 41.4, 20.6, 19.3 and 18.7%, respectively in Typic Ustochrept. In comparison with control, system receiving farmyard manure (FYM-10 Mg ha⁻¹ season⁻¹) alone showed greater C build up (40.5%) followed by 100% NPK+FYM (120:60:40 kg N, P, K ha⁻¹+ 5 Mg FYM ha⁻¹ season⁻¹) (16.2%). In addition, with 50 per cent NPK (-1.2 Mg ha⁻¹) and control (-1.8 Mg ha⁻¹) treatments, a net depletion of carbon stock was observed. Just 28.9 per cent of C applied through FYM has been stabilized as SOC in double rice cropping system.

7. CONCLUSION

This review paper concludes that the application of fertilizers and/or FYM resulted in greater C sequestration in cereal systems of semi-arid agricultural soils. The accumulation of SOC was greater in the surface layer of the soil as compared to subsurface layer due to the greater accumulation of the organic residues and external additions of organic matter at the surface layer. The integrated and organic treatments significantly increased the aggregate dynamics, water stable aggregate, soil organic carbon and SOC fractions, as compared to the chemical fertilizers alone. This suggests that the inclusion of organic manures in fertilization programs have the most beneficial effects on the production of carbon pools, improve the availability of SOC and also enhance C sequestration in soils. Therefore, organic matter plays a key role in the global carbon balance which is known to be the main factor influencing global warming. Overall, sufficient quantities of soil organic matter improve soil quality, preserve sustainability of cropping systems, and reduce environmental pollution.

The average control treatment SOC concentration was 0.54 percent, which increased to 0.65 percent in RDF treatment and 0.82 percent in RDF+FYM treatment affects the dynamics of soil nutrients under field conditions. A regular input of biomass-C along with chemical fertilizers is essential to improving soil quality in the agro ecosystems particularly in semi arid tropics of India and for minimizing the depletion

of SOC stock under continuous cropping. Use of organic amendments is essential to enhancing the SOC sequestration. The minimum input of 1.1 Mg C ha⁻¹ year⁻¹ is needed to maintain SOC at the initial level. In view of the decreasing availability of FYM, however, application of 10.7 Mg ha⁻¹ of FYM (equivalent to 60 kg N) on dry weight basis is difficult. Thus, conjunctive use of FYM or other crop residues along with 50% recommended dose of fertilizers is a viable option for curbing SOC depletion and sustaining crop production. Hence, balanced use of NPK fertilizer along with FYM or other crop residues, which will take care of critical-C-input addition quantitatively, will be a better option to stop SOC depletion and maintain and sustain crop production.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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