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Soil Carbon Pools, Carbon and Nitrogen Storage Pattern in Soil Aggregate Fractions under Long-term Application of Organic and Synthetic Fertilizers in Rice-Wheat System: A Review

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Authors' contributions

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

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Review Article

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ABSTRACT

Soil organic matter (SOM) has long been recognized as an important indicator of soil productivity. The SOM refers to the organic fraction of undecayed plant and animal residues. The preservation of SOM is crucial to ensure long-term sustainability of agricultural ecosystems. OM plays a critical role in the global carbon balance that is thought to be the major factor affecting global warming. Overall, adequate amounts of SOM maintain soil quality and reduce environmental pollution. SOC concentrations and storage to 60 cm depth are significantly influenced due to long-term fertilization. The SOC storage in 0–60 cm in NP+FYM (farmyard manure), NP+S, FYM and NP treatments were increased as compared to the CK treatment. The 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 increased linearly with increasing SOC content. Light fraction organic carbon (LFOC) was also significantly higher following

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the treatments including organic amendment than following applications solely of chemical fertilizers. Application solely of chemical fertilizers had no significant effects on LFOC and $KMnO_4C$ fractions compared with unfertilized control plots. Carbon pools were significantly correlated with SOC, which increased with application of organic amendments. Threshold C input of 3.3 $MgCha^{-1}$ yr^{-1} was needed to maintain the SOC stock even at the low antecedent level. This review study will be helpful in crafting sustainable nutrient management programs in the future to enhance crop productivity with high efficiency and minimum nutrient loss. Therefore, fertilization strategies that include organic manure can increase the pool of stable C in the surface soil layer, while at the same time increasing concentrations and proportions of labile C. Organic manure use contributes to improved nutrient cycling services and higher soil quality in rice-wheat system.

Keywords: Mineralization dynamics; aggregate fractions; organic matter fractions.

1. INTRODUCTION

Agro-ecosystem represents around 40% of all land on earth[1], which is critical for maintaining agricultural sustainability, environmental stability, and long-term terrestrial carbon (C) sequestration [1,2]. Soil organic carbon (SOC) and its labile fractions are strong determinants of improving soil chemical, physical, and biological properties and plays a major role in the recycling of plant residues affecting soil organic matter levels and soil quality [3]. Fertilization as an agricultural management strategy, is being used to promote soil C storage [4,5], which could directly or indirectly increase the SOC inputs and thereby change the availability of nutrients and soil turnover [6]. For instance, inorganic nitrogen (N) fertilizer may indirectly enhance the SOC storage by increased crop residue input to soils [4,7], whereas application of organic manure could influence soil organic matter (SOM) owing to the directly inputs of processed organic materials to soils [8]. In contrast, application of organic fertilizers would result in a higher level of soil C and N mineralization than inorganic fertilizers [8,9]. Generally, soil C turnover mainly depends on the interplay between organic inputs and decomposition of SOM with positive, neutral, or even negative response to fertilizer additions [10].

Light fraction organic matter, which is a transitory pool between fresh residues and the humidified organic soil [11], is known to be a significant pool for soil organic matter turnover. Many researchers have concluded that practically all C compounds are susceptible to metabolism by microorganisms within a relatively short time of being introduced to soil [12,13]. If this is true, the idea of recalcitrant compounds resisting breakdown and thereby becoming part of the slow turnover pool organic matter in soil can be tested by adding an assortment of compounds and determining how long they persist and increase SOC. The incorporation of organic residues into the soil increases biological activity [14] and organic carbon [15] plays a role in greater contribution to organic matter in the accumulation of total organic carbon (TOC) in the superficial layer of the soil, and also improve soil conservation, compaction and future soil fertility [16,17]. Organic residue is utilized by soil microorganism and fauna as a source of nutrient and energy for better soil quality [18].

The distribution and stability of soil aggregates are important soil physical quality indicators, emphasizing the significance of soil management in particle aggregation and disaggregation [19]. SOC sequestration is mainly due to micro-aggregates (0.05–0.25 mm) since they are stabilized by persistent binding agents (> 0.25 mm) and by transient binding agents, macro-aggregates are stabilized [20]. Long-term use of organic fertilizer often increases SOC content [21] and the proportion of macro-aggregates [22]. Reports of the effect of organic fertilizer on the distribution of micro-aggregates, however, have been inconsistent. Tripathi et al. [23] found that the use of organic fertilizer, compost, and manure in the farmyard reduced the proportion of micro-aggregates significantly, respectively. Interestingly, some studies have shown that organic fertilizer has no substantial influence on the micro-aggregates relative to an unfertilized control [24]. Here, we hypothesized that the usage of mineral fertilizer and organic materials would change SOC and its fractions, and improve aggregate stability. Specifically, we sought: (i) To determine the characteristics of SOC fractions, carbon and nitrogen storage pattern, and aggregate stability mean weight diameter (MWD) under a long-term application of fertilization; (ii) to understand the role of SOC fractions and soil carbon and nitrogen storage pattern.

2. SOIL ORGANIC CARBON (SOC) TRENDS

Liu et al. [24] reported that the maximum concentration of SOC was obtained at depths 0-20 cm and decreased with depth for all treatments. The concentration of SOC in 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 highest in NP+FKM followed by treatments with NP+S and FYM and the least in treatment with CK. However, the concentration of SOC below a depth of 60 cm was statistically similar among different treatments. The application of fertilizers and/or FYM resulted in greater C sequestration and also increase the accumulation of SOC was higher 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 [3]. Bhattacharyya et al. [25] showed that addition of farmyard manure (FYM) with Nitrogen (N) or NPK fertilizers increased SOC contents. The overall gain in SOC in the 0- to 45-cm soil depth interval in the plots under farmyard manure plus N, P and K fertilizers (NPK + FYM) treatment over NPK was 17.18 Mg C ha^{-1} in 30 year. The rate of conversion of input C to SOC was about 19% of each additional Mg C input per hectare. SOC content in large size aggregates was greater than in smaller size aggregates and declined with decreased aggregate size.

Ghosh et al. [26] revealed that wheat based cropping, plots under farmyard manure plus N, P and K fertilizers (NPK + FYM) had~19% and 138% higher total SOC concentration than NPK and control plots, respectively, in the 0–15cm layer soil surface. However, plots with 150% NPK and NPK treatments had similar total SOC concentrations in that layer. Similarly, plots under NPK + FYM had: a)~136% and 24% greater SOC concentration in the 15–30 cm layer; b)~130% and 18% more SOC concentration in the 30–60 cm soil layer; c)~80% and 29% higher SOC concentration In a layer of 60-90 cm than control and NPK plots, respectively. In General, plots with NP had significantly higher total SOC concentrations than the plots with N, in all the soil layers.

Ghosh et al. [27] observed that the plots with 50% NPK fertilizers + 50% farmyard manure (FYM) had significantly higher SOC content followed by 50% NPK fertilizers + 50% Green manure (GM) in topsoil. The lowest bulk SOC was found with the control plots in topsoil. Significantly higher (+35 and 38%) SOC, in both soil layers was recorded with 50% NPK +50% FYM over the control treatment. 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.

Shahid et al. [28] revealed that as compared to the initial (13.7 Mg ha^{-1}), the SOC stock in 0–15 cm depth increased under all the fertilized treatments during 41 year period in the order: NPK + FYM > N+FYM> NPK> FYM> N> control. Thus, the rate of increase in SOC stock due to fertilizer application alone varied between 57 and 89 kg ha^{-1} yr^{-1}, while for FYM addition the rate of increase was 61 to 138 kg ha^{-1} yr^{-1}, highest being in NPK + FYM. Anshori et al. [29] reported that the organic carbon contents of organic and conventional rice fields were significantly different, 0-4 cm layer , 4-8 cm layer 8-12 cm layer, 12-16 cm layer, 16-20 cm layer and 20-24 cm layer in Inceptisols. The organic carbon at all depths of top soil of organic rice field were significantly higher than the contents in conventional rice field, because of the application of organic fertilizer in organic rice management and synthetic chemical fertilizers in conventional rice management. Stratification of soil organic carbon content was also found by Zhang et al. [30]; Mujiyo et al. [31] and Anshori et al. [32]. Stratification of organic carbon in top soil of organic and conventional rice fields because of the application of organic fertilizer in organic rice management and synthetic chemical fertilizers in conventional rice management. Li et al. [33] revealed that treatments which received organic manure had significantly higher SOC concentrations compared to the mineral and control treatments as much as 35.39 Mg ha^{-1} more C in the top 20cm than the CK treatment. Furthermore, SOC concentrations significantly increased with increasing manure input rates. The lowest SOC concentrations were observed in the CK treatment.

3. FRACTIONS IN SOIL C

The Particulate organic carbon (POC) fraction was identified as a labile SOC pool consisting mainly of partially decomposed plant residues which are not associated with soil minerals [34]. In the 0-60 cm, the soil modified by FYM or straw contained considerably higher POC than that in the inorganic fertilizer treatments. Rudrappa et al. [35] reported that the additional organic carbon input could increase POC accumulation, it was reported. Purakayastha et al. [36] concluded that the root biomass and microbial biomass debris which is the main source of particulate organic carbon (POC) can be increased by FYM. It is suggested that root litter should have a greater biochemical recalcitrance [37] POC content in soil might also have increased depending on the root biomass produced. The continuous replacement of organic manure on the soil creates a favorable weather patterns for C cycling and macro-aggregate formation. Particulate organic carbon (POC) also acts as a cementing agent for stabilizing macro-aggregates and for protecting intra-aggregate C in the form of POC [34]. With soil depth increased, the POC decreased below 60 cm of soil layer. Chan [38] (1997) also found that straw application increased POC but not at lower depths in surface soil.

Zhu et al. [39] also found that soil TOC and labile organic C fractions contents were significantly affected by straw returns, and were higher under straw return treatments than non-straw return at three depths. At 0–7 cm depth, soil microbial biomass carbon (MBC) was significantly higher under plowing tillage than rotary tillage, but easily oxidizable C (EOC) was just opposite. The increase in these C fractions was greater when farmyard manure (FYM) was applied in combination with 100% NPK treatment showing the highest amount of SOC and POC in soil depth of 0–45 cm. The application of manure substantially increased the proportion of large macro-aggregates (> 2000 μm) relative to the regulation, while resulting in a corresponding decrease in the percentage of micro-aggregates (53–250 μm). The NPK+FYM plots had highest recalcitrant C pools within macro-and micro-aggregates. Moreover, carbon fractions of soil organic carbon (SOC), particulate organic carbon (POC), microbial biomass carbon (MBC), and potential carbon mineralization (PCM), the aggregate proportion was greater in no-tilled continuous spring wheat (NTCW) than in fall- and spring-tilled continuous spring wheat (FSTCW) in the 4.75- to 2.00mm aggregate-size class at 0 to 5 cm but was greater in spring-tilled spring wheat-fallow (STW-F) than in spring-tilled continuous spring wheat (STCW) in the 2.00- to 0.25-mm size class at 5 to 20 cm [40].

Naresh et al. [41] reported that the maximum SOC concentration for all treatments was obtained at a depth of 0–5 cm and decreased with the sub-surface depth. The concentration of SOC at depths of 0–5 and 5–15 cm increased significantly by application of farmyard manure or GM / SPM. At soil depths of 0–5 and 5–1 cm, SOC was the highest in 50 percent RDN as CF+50 percent RDN as FYM (F5), followed by 50 percent RDN as CF+50 percent RDN as GM/SPM (F6) and the lowest in Control (no manure and fertilizer) F1. The total 0-15 cm layer SOC stocks were 35.17 Mgha-1 for 50 percent RDN as CF+50 percent RDN as FYM-treated soils, compared with 28.43 Mgha-1 for 100 percent RDN as CF-treated plots and 26.45 Mg ha-1 for unfertilized control plots. Soil organic C content in the 0–15 cm soil layer in the plots below 50 per cent RDN as CF+50 per cent RDN as FYM treatment was 16 per cent higher than that of the plots treated as CF+25 per cent RDN under 75 per cent RDN. The TOC in surface soil was in the order of 50 percent RDN as CF+50 percent RDN as FYM (23.65 gkg−1) > 50 percent RDN as CF+50 percent RDN as GM / SPM (21.47 gkg−1)>1/3rd N as CF+1/3rd N as FYM+ 1/3rd N as GM / SPM (21.40 gkg−1)>75 percent RDN as CF+25 percent RDN as FYM (19.64gkg-1) > unfertilized control (10.99 gkg−1) > unfertilized control (10.99 gkg−1). However, the increase in TOC was more in surface compared to sub-surface soil, which indicates that higher accumulation of organic carbon was confined to surface soil due to application of organic fertilizer. The increase in TOC in organic + inorganic fertilizer in surface layer as FYM and GM / SPM treatments was 53.5 and 48.8 percent over unfertilized control, while 24.8 and 17.2 percent were higher than 100 percent RDN as CF treatment , respectively. This could be due to more root biomass turn-over in 50% RDN as CF+50 percent RDN as FYM treatment due to better growth and higher average yields obtained in 50% RDN as CF+50 percent RDN as FYM treatment as compared to 50% RDN as CF+50 percent as GM / SPM treatment.

4. SOIL LABILE ORGANIC C FRACTIONS

Labile organic carbon is the portion of soil organic carbon that can be readily decomposed by soil organisms [42]. Farm productivity is closely linked to soil functions that depend on the amount and quality of labile organic carbon and its turnover rate. Labile organic carbon can be a sensitive soil alteration indicator in soil health in response to land management change. Changes in labile organic C fractions can respond to soil management practices more quickly than total SOC content [43]. It has been widely accepted that application of organic manure markedly increases labile organic C fractions [44,45], which is consistent with our findings. The DOC is mobile within the soil solution and is thus considered to be the most bioavailable source of C substrates for microbial populations [46]. Li et al. [47] reported that the effects of fertilization on soil labile organic C showed a similar trend to total SOC. The contents of DOC, LFOC, and MBC were respectively 264%, 108% and 102% higher after NPSM application, and respectively 57%, 82% and 38% higher after NPS application than compared with those of CK.

Awanish, [48] 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. 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 $F_4>F_1>F_2>F_3$. 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 (F_1) which was contributing around 40% or more in surface and surface (0–5 and 5–15 cm) layers 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. Zhang et al. [49] also found that application of inorganic fertilizer, straw with inorganic fertilizer, manure, and manure with inorganic fertilizer increased soil microbial biomass carbon (C_{mic}) concentration, while nitrogen-only (N) and nitrogen plus manure (NM) decreased soil microbial biomass nitrogen (N_{mic}) concentration compared with control (no fertilizer application). Many inorganic fertilization treatments (NPK, NP, and PK), NPKS and all manure fertilization treatments (NPKM, NPM, NKM, NM, and M) had significantly positive effect on C_{mic}, other fertilization treatments had either significantly positive or insignificant effect on C_{mic}. The greatest MD in N_{mic} occurred under NPKS and NPKM treatments, both with increases in N_{mic} of 1.41 mg kg^{-1}, while the lowest significant MD was obtained under NPK treatment, with an increase of 0.29 mg kg^{-1} compared with that of the control treatment. The N_{mic} values for NPKS and NPKM Treatments is significantly greater than the treatment with NPK. Organic carbon concentrations in the < 0.053-, 0.053-to 0.25-, 0.25-to 2.0 fractions and > 2.0-mm fractions were respectively 14.0, 12.0, 14.4, 24.1 per cent higher in conservation agriculture than in chemical fertilizers (CF). The contents of soil organic carbon (SOC), Labile organic carbon (LOC), dissolved organic carbon (DOC), particulate organic carbon (POC) and easily oxidizable carbon (EOC) by 14.73%, 16.5%, 22.5%, 41.5% and 21% in the soil layer of 0-40 cm, and 17%, 14%, 19%, and 30% in the soil layer of 0-100 cm. These results suggest that, over time, MBC and MBC-derived C may be a significant source of stable SOC through strong physical and chemical bonding with the mineral soil matrix [40].

Krishna et al. [50] (2018) reported 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 (Table 1). In comparison with control, system receiving farmyard manure (FYM-10 Mg ha^{-1}season^{-1}) alone showed greater C build up (40.5%) followed by100% NPK+FYM (120:60:40 kg N, P, K ha^{-1}+ 5MgFYMha^{-1} season-^{1}) (16.2%). In fact, a net depletion of carbon stock was observed with 50% NPK (-1.2 Mg ha^{-1}) and control (-1.8 Mg ha^{-1}) treatments. Only 28.9% of C applied through FYM was stabilized as SOC. A minimal input of 2.34 Mg C ha^{-1} yr^{-1} is needed to maintain SOC level. 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. 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).

Table 1. Oxidizable organic carbon fractions (very labile, labile, less labile and nonlabile) in soils (g kg^{-1}) at different layers (cm) under the treatments studied. [Source: Krishna et al., 2018. [50]

Treatment	Very labile C				Labile C			
	0-5	15-30	30-45	Total	0-5	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^{a}	1.3±0.3^{a}	8.1±0.2^{a}	1.9±0.3^{ab}	0.7±0.2^{a}	0.7±0.3^{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±0.2^{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}	1.0±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^{d}	1.2±0.5^{b}	1.2±0.3^{a}	1.2±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^{cd}	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±0.3^{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±0.2^{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}

**Values in the same column followed by different letters are significantly different at P<0.001 according to Duncan's Multiple Range Test (DMRT) for separation of means, ± indicates the standard deviation values*

5. SOIL ORGANIC CARBON STORAGE

Habteselassie et al. [51] 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 54% as compared with ammonium sulfate and liquid dairy-waste treatments, respectively, applied at the same available N level (200 kg Nha^{-1}). This C stored in the soil organic matter accounts for approximately 11% of the total amount of C applied. Under 7–36-year fertility experiments in five different rice based cropping systems, the application of organic amendments at 5–10 t ha^{-1} year^{-1}, through farmyard manure or compost combined with balanced mineral NPK, increased organic carbon by 10.7% [52]. In a rice–wheat system, farmyard manure application at 20 t ha^{-1} showed, after a period of 32 years, higher organic carbon concentration of 17% compared with NPK fertilizers in the 0–15 cm soil layer [53]. Nevertheless, the results of repeated applications of either digested sewage sludge over 12 years or farmyard manure for 40 years indicated that such organic amendments were inadequate for restoration of organic matter lost as a consequence of cultivation [54]. In fact, the amount of organic carbon in the undisturbed site was 120 and 156% higher than that in farmyard and sludge cultivated soils, respectively. On the other hand, contrary to common belief, over a 25-year period of intensive rice-wheat cropping, a depletion of organic carbon did not occur, but rather an improved organic carbon concentration of 38% [55].

According to Sodhi et al. [56], a 10-year application of rice straw compost, either separately, or in conjunction 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. Nardi et al. [57] also found that, over 40 years, farmyard manure fertilization improved by 116% the production of humus with a high degree of poly-condensation, a high-quality fraction usually linked to soil fertility. Conversely, the absence of organic fertilizer inputs determined the opposite, with a higher percentage of non-complex and light weight humus.

Srinivasarao et al. [58] reported that in the surface 0.2m 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) (2.2gkg^{-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 organics and in-organics or sole FYM treatments. The lowest SOC concentration (1.3 g kg^{-1}) in 0.2m depth was observed in treatment of a continuous cropping of pearl millet, cluster bean and castor over 18 years without any amendments. The mean SOC concentration in the profile increased from 1.2 gkg^{-1} in control to 1.8 g kg^{-1} in 50 per cent RDN (F) + 50 per cent RDN (FYM). Despite these increases, the SOC concentration remains below the threshold level required for a good soil health. Significant variations in SOC concentration were observed even in the subsoil layers. The mean SOC concentration decreased from 1.8 g kg^{-1} in the surface 0.2mlayer to 1.1gkg^{-1} in the 0.8–1.0m depth. The highest C inputs through crop residues was measured in 50 per cent RDN (F) + 50 per cent RDN (FYM) (6.6 $Mgha^{-1}$), followed by that in 100 per cent RDN (F) (6.3 $Mgha^{-1}$), and the lowest in control (3.7Mg ha^{-1}). Combined with the external C inputs through FYM, total C inputs ranged between 3.7 Mg ha^{-1} in control to 33.5$Mgha^{-1}$ in 50 per cent RDN (F) + 50 per cent RDN (FYM). The magnitude of C inputs through crop residues was in proportion to the nutrients applied.

Cai et al. [59] reported that long-term manure with/without chemical fertilizer application substantially increased the SOC content in all particle size fractions of the soil while the usage of chemical fertilizer alone (M_0N, M_0NPK) did not alter the SOC content in any particle size fraction of the soil relative to the control (CKM0). Compared with no application of manure (M_0), the annual application rate for manure of 30 and 60 t ha^{-1} increased the SOC in soil fractions by 20–60% (M_{30}) and 52–115% (M_{60}), respectively. Under the M_{60}NPK treatment, the highest volume of SOC (45.1 $gCkg^{-1}$ fraction) occurred in the fraction of particle size 2000–250μm. Bhardwaj et al. [60] also found that budgeting total plant assimilated C and C-input into soil, revealed that the maximum C was assimilated in GM (22.3 Mg ha^{-1}) followed by LE (18.6 Mg ha^{-1}), F (16.2 Mg ha^{-1}), FYM (14.0 Mg ha^{-1}), WS (13.5 Mg ha^{-1}), RS (13.3 Mg ha^{-1}), and O (6.3 Mg ha^{-1}). Carbon input into the soil also varied in the same order. The maximum input of C into soil was in GM (8.0 Mg ha^{-1}) followed by WS (4.5 Mg ha^{-1}), RS (4.5 Mg ha^{-1}), LE (4.4 Mg ha^{-1}), FYM (3.0 Mg ha^{-1}), F (2.5 Mg ha^{-1}) and O (0.9 Mg ha^{-1}). The C input into the soil as the percentage of C assimilated in the system was maximum in GM (36%) and least in O and F (15%).

Singh et al. [61] reported that the SOC content increased under OF, IPNS and IPNS+B or C over the years but declined in the control plots. The SOC remained unaffected under RDF during the different years of study. During the terminal year the maximum SOC (6.9 g kg^{-1}) was noticed under OF which was much higher than that under IPNS (6.2 g kg^{-1}) and IPNS+B or IPNS+C (6.4 g kg^{-1}). The RDF and control plots had significantly lower SOC contents than the different IPNS options. The SOC content also varied with soil depth, and a relatively lower SOC was noticed at the15–30 cm depth. At this soil depth, IPNS combined with legumes had a significant edge over OF in different years of the study. The SOC, measured after 20 annual RW cycles vis-à-vis the onset of the experiment, showed improvements of 6–39% and 19–74% at the soil depths of 0–15 and 15–30 cm, respectively, in all treatments except for the control, wherein the SOC declined by 14–35% from its initial value.

6. MICROBIAL BIOMASS CARBON (MBC)

The Microbial Biomass Carbon (MBC) is an essential component of the SOM controlling nutrient transformation and storage. The MBC soil governs all transformations of SOM and is considered the chief component of the active SOM pool. It is evident that the MBC content in both surface and sub-surface soil was substantially higher in plots receiving a 50 percent recommenced dose of Nitrogen (RDN) as Chemical Fertilizers (CF)+50 percent RDN as Farmyard Manure FYM (F_5) and a 50 percent recommenced dose of Nitrogen (RDN) as Chemical Fertilizers (CF)+50 percent RDN as Green Manure GM/SPM (F_6) treated plots compared to a 100 percent dose of Nitrogen (RDN). MBC values in surface soil ranged from 116.8 mgkg−1 in unfertilized control plots to 424.1 $mgkg^{-1}$ in integrated nutrient use of 50 percent RDN as CF+50 percent RDN as FYM (F_5) plots, respectively; whereas they ranged from 106.6 $mgkg^{-1}$ (control) to 324.9 $mgkg^{-1}$ (50 percent RDN as CF+50 percent RDN as FYM F_5) in sub-surface soil layers (5-15 cm). MBC values fell by 58.4 and 72.5 per cent below 75 per cent RDN as CF+25 per cent RDN as FYM (F_3) and 50 per cent RDN as CF+50 per cent RDN as FYM (F_5) treatments over control in surface soil. Although MBC increased by 14.5 and 43.4 per cent over 100 % RDF as Chemical fertilizer (CF) (F_2), respectively. MBC's highest value due to integrated use of FYM and RDN fertilizer may be due to higher turn-over of root biomass generated as CF+ 50 percent FYM treatment under 50 percent RDN [41].

Application of 100% RDN as CF fertilizer is required not only for better crop growth but also for the synthesis of microorganism cellular components. Lower root biomass under 50 percent RDN as a CF+50 percent FYM fertilizer treatment therefore helped to improve MBC over other treatments. While MBC content in soil represents a small fraction, i.e. approximately 2-4% of TOC, variations in this pool due to management and cropping systems indicate the quality of soil, because SOM turn-over is regulated by this pool of SOC which can provide an important early warning of improvement or deterioration in soil quality as a result of different management practices. The increase of MBC under FYM amended soils could be due to several factors, such as higher humidity content, higher soil aggregation and higher SOC content. The FYM modified plots provided a steady supply of organic C to sustain the microbial community as opposed to the plots treated with inorganic fertilizer. Generally, FYM applied to soil has typically been employed for a long time to improve favorable soil conditions [41].

Chakraborty et al. [62] observed that the MBC was highest in the 100% RD of NPK+FYM treatment (431μgg^{-1}) but was statistically similar to the 150% NPK treatment (392μgg^{-1}). The MBC in the 100% RD of NPK treated soil (364μgg^{-1}) was slightly lower than the 150% RD of NPK treatment. Among the exclusive mineral fertilizer treatments, the 100% N treatment recorded the lowest MBC (306μgg^{-1}). Of all the treatments, the untreated control produced the lowest MBC (223μgg^{-1}). Urea along with FYM increased MBC as FYM supplied readily available organic matter besides increasing root exudates and root biomass due to greater crop growth. MBC is highly correlated with the soil organic matter which is in accord with Anderson and Domsch [63]. The BSR reflects the catabolic degradation of soil microbial communities under aerobic conditions. It decreased according to the order of100% RD of NPK+FYM>150% RD of NPK>100% RD of NPK>100% RD of N>untreated control. However, the BSR measured in the treatments 100% RD of NPK+FYM (1.96μg CO_2–Cg^{-1}soil h^{-1}) and 150% RD of NPK (1.65μg CO_2–Cg^{-1}soil h^{-1}) did not differ statistically. The 100% RD of N (1.37μg CO_2–Cg^{-1}soil h^{-1}) and 100% RD of NPK (1.08μg CO_2–Cg^{-1}soil h^{-1}) treatments had statistically similar values of BSR. Inorganic supplements exclusively may fulfill the demand for mineral nutrition but not the carbon for cell proliferation by the microorganisms. Integrated use of of organic manures and inorganic fertilizers brings in more MBC in soil compared to exclusive inorganic fertilizer applications [64].

Katkar et al. [65] also found that an application of NPK+ farmyard manure at 10 tonnes/ ha recorded significant increase in biological parameters, viz soil microbial biomass carbon (SMBC), soil microbial biomass nitrogen (SMBN) and dehydrogenase activity (DHA) to the extent of 8.8, 9.3 and 9.0% compared to 150% NPK through chemical fertilizers without organics. This can be ascribed to direct addition of organic matter through farmyard manure and increase in root biomass which helped in growth and development of soil micro-organisms causing beneficial effect on SMBC, SMBN and DHA. Application of farmyard manure at 10 tonnes/ha (only to sorghum) significantly increased SMBC, SMBN and DHA over control which might be due to a steady source of organic carbon to support the microbial community [25]. The lowest value of SMBC was observed in the control obviously due to unfavorable environment arising out of depletion of nutrients due to continuous cropping without any fertilization or manuring. The highest SMBC in the INM treatments was due to additional carbon which is mineralizable and readily hydrolysable from farmyard manure [66]. The soil microbial biomass nitrogen decreased at 100% NP and 100% N to the tune of 17.6 and 24.8% compared to100% NPK (T_2) indicating necessity of balanced fertilizer application for enhancing soil microbial activity. It was further observed that combined use of farmyard manure at 10 tonnes/ha with 100% NPK increased microbial biomass nitrogen by 17.3% compared to NPK indicating augmented effect of organics in microbial activities. High soil organic carbon, more root proliferation and additional supply of N by farmyard manure to micro-organisms might be responsible for increasing the level of SMBN [65].

Moharana et al. [67] revealed that the MBC soil regulates all SOM transformations and is regarded as the chief component of the active SOM pool. It is obvious that in plots receiving FYM+NPK and FYM treated plots, the MBC content in both surface and sub-surface soil was significantly higher compared to the NPK fertilizer and unfertilized control plots. MBC values in surface soil ranged from 155 mg kg−1 in unfertilized control plot to 273 mg kg^{-1} in integrated nutrient use of FYM+NPK plots, respectively; whereas they ranged from 113 mg

kg^{-1} (control) to 156 mg kg^{-1} (FYM + NPK) in subsurface soil. Manjaiah and Singh [68] registered an increase in MBC by a factor of three following a combined application in a semiarid Cambisol of FYM and mineral N-fertilizer. The higher microbial biomass in FYM+NPK may be both attributed to higher residues of plants below ground as well as FYM added. Srinivasarao et al. [58] revealed that among fertility treatments, the highest profile mean MBC was measured in 50 per cent RDN (F) + 50 per cent RDN (FYM) (82.6 mgg^{-1} soil) followed by that in 50 per cent RDN (FYM) (62.8 mgg^{-1} soil), and the lowest in control (45.2 mgg^{-1} soil). Pant et al. [69] also found that the conjoint [] application of 100% NPK and FYM arrested the highest contents of carbon in different active pool followed by 150% NPK. High soil carbon content, more root proliferation, and additional supply of N by FYM to microorganisms are responsible for increasing different carbon fraction in organically amended plots with control, fertilizers, treated plots contained one to three times more TOC, MBC, one to two times more MBC, WSC, HWEC, and two to seven times more POC in soil after rice harvest but lesser amount in after wheat harvest. This indicated that POC can act as a considerably sensitive indicator of crop sequence and soil management practices.

7. CONCLUSIONS

This review study clearly indicated that various applied organic fertilizers significantly increased total SOC contents and labile organic C fractions (Dissolved organic carbon (DOC), light fraction organic carbon (LFOC) and microbial biomass carbon (MBC)) in agricultural soils. Moreover, the greatest increases were observed in treatment with the combined applications of manure, straw and mineral fertilizers. Organic fertilization also slightly altered the composition of microbial communities. Furthermore, the application of organic fertilizers resulted in 53%-85% greater cumulative mineralization of C. Application of fertilizers has been critical in enhancing the total content of SOC and labile C pools in the soil. The long term use of organic manure and inorganic fertilizer increased the SOC content. Under NP+FYM and NP+S, SOC concentrations and storage were the highest in surface soil and depth intervals down to 60 cm, below which concentrations did not change with depth. At the same time, the soil C storage estimate at 60 cm depth was on average higher than that obtained at 20 cm depth and 40 cm depth for soil C, respectively. All these results indicate that soil C accumulation estimates at a depth of 60 cm were more accurate than those for soil C accumulated at a depth of 20 cm and 40 cm. NP+FYM represented the most effective SOC sequestration management system. Under NP+S treatment a significant volume of C was also sequestered in the soil. Under organic manure (farmyard manure or straw), plus inorganic fertilizers, particularly on the surface, soil microbial biomass C, POC, and DOC were all significantly greater. The organic content of the labile fraction C decreased significantly with increased depth of soil. These labile pools were highly correlated with each other and with SOC, indicating being sensitive to SOC changes.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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