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Soil aggregates bound organic carbon fractions and their mineralization

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ABSTRACT

Soil organic carbon (SOC) plays a vital role in maintaining soil health and nutrient mineralization in longer duration of time. The fractions of soil organic carbon behaved differently to the course of management for the crops. The application of nutrients in the form of organic or inorganic or integrated nutrient management (INM) in maintaining higher productivity is well understood and it is the practice that is needed for sustainable agriculture. Aggregates holds carbon for longer duration and helps in carbon stabilization along with helping in establishment of good crop stand and favorable physical environment in root zone. Poor soil aggregation, instability, loss of water-holding capacity, fertility, enzymatic activity, and soil biology are all consequences of SOC depletion. There is a crucial need to evaluate globally the response of soil aggregates and aggregates bound organic carbon and its fraction by long term application of manure and fertilizers to understand distribution of aggregates with changing fertilization management. The changes in the soil properties due to implementation of any management practices can be deeply understood through the long-term studies. Organic manure alone contributed maximum amount of organic carbon in soil which was followed by 50% organic manure and 50 % through inorganic fertilizers. Conservational tillage operations contributed more to labile fractions of organic fractions than conventional tillage. Here, in this study we reviewed soil organic carbon, soil organic carbon fractions as labile and recalcitrant fractions and soil organic carbon mineralization in different size soil aggregates (macro and micro aggregates) under the influence of Farm yard manure (FYM) and inorganic fertilization in longer duration.

Key words: Soil aggregates, Soil organic carbon fractions, integrated nutrient management, Carbon mineralization, long-term experiments

INTRODUCTION

The number of people living off the earth's resources and stressing its ecosystem has doubled in just few years. By 2050, our population is expected to grow from 7.6 billion to 10 billion (Baillie and Zhang 2018). Therefore, the very first question that comes into people's mind is that, if there is enough food for all of us in future. The country has achieved self-sufficiency in food production through the adoption of modern technologies, intensive cultivation of soils, taking high-yielding varieties and inclusion of multiple cropping systems. But in this process, soil has been extensively exploited. Both the over- and under-application of fertilizers and the poor management of resources, not only deteriorated soil health, but also raised environmental concerns (Mahajan *et al.* 2009) So, we require effective and efficient approaches to maintain crop productivity for sustainable agriculture. The overall strategy for maintaining sustainable crop yield includes an integrated approach of management of soil nutrients, along with other complementary measures. To maintain the fertility and productivity of soil at a sustainable level, there is need to adopt the concept of integrated nutrient management. The integrated nutrient management improves physical properties such as soil structure, aeration, porosity, infiltration rate and water holding capacity and decrease soil crusting. The use of organic manures and fertilizers in an integrated manner could be the most logical strategy for maintaining the soil productivity, fertility and sustaining the soil health and quality on long term basis (Dev Raj *et al.,* 2013). Addition of organic matter either in the form of crop residues or organic manures improves the organic carbon status in soil (Antil *et al.,* 2011) which is a key component in maintaining the soil physical, chemical & biological properties to an optimum level. Soil organic carbon can be divided into several fractions depending on their densities. Labile fraction is the most prominent, partly due to its high turnover rate plus it is easily affected by management systems as well as erosion (Wang

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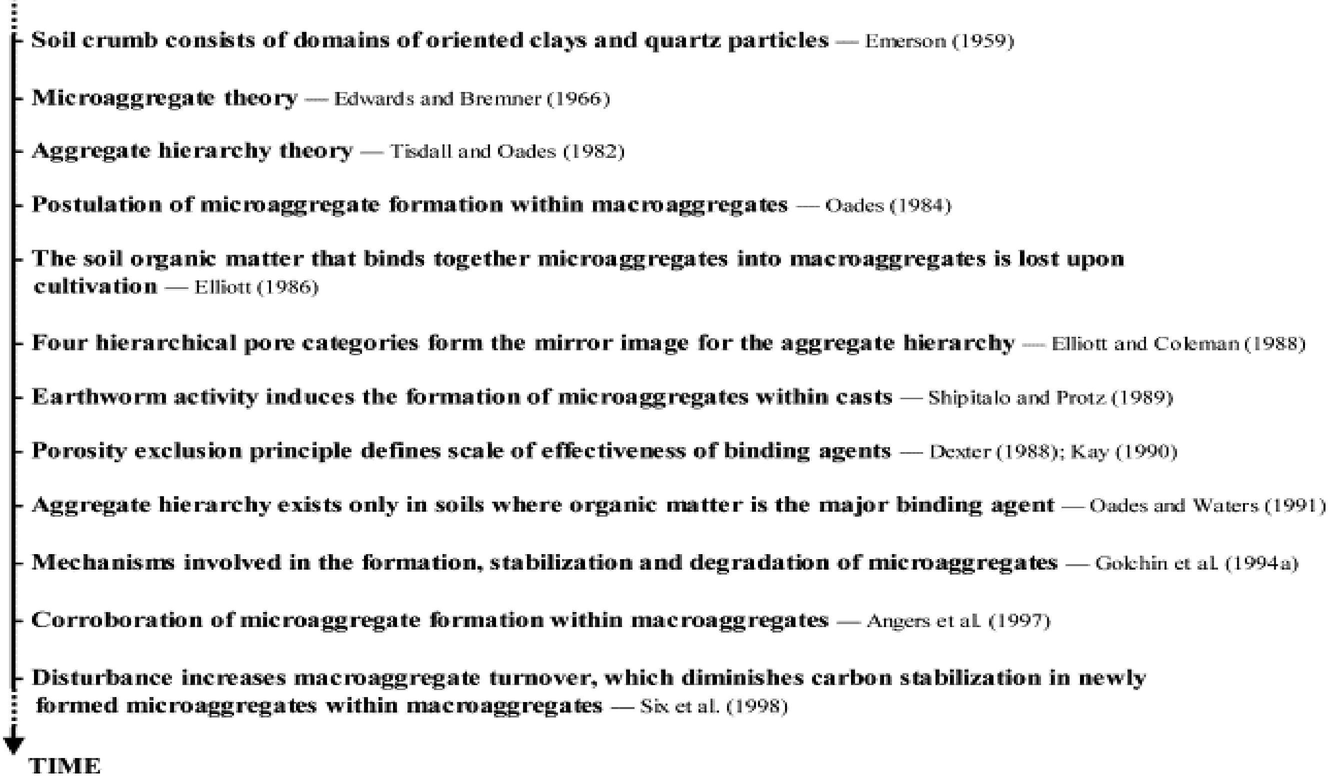
et al., 2014). Soil organic carbon promotes soil structure and aeration by improving aggregate formation. The formation and stability of aggregates are inextricably linked to soil organic carbon (Tisdall and Oades 1982). The organic carbon fractions of soil are key binders in the formation of aggregates (Six *et al.,* 2002). Soil aggregation and structure are important aspect of soil fertility through influencing root distribution and uptake of water and nutrients (Bronick and Lal 2005). The stability of organic carbon in different size aggregates is different. Soil aggregates interacted with soil organic matter and thereby with the soil organic carbon in many ways. This was studied in details since long time and researchers have different opinion from history till today about the interaction of soil organic matter and aggregates formation (Fig 1). Organic carbon in micro-aggregate is less susceptible to change than it is in the macro-aggregates. According to Bolan *et al.* (2011) labile organic matter in soil mostly results from the decomposition of dead microbial biomass, root exudates, and plant and animal biomass. The labile carbon (Active pool) pool of SOC is readily accessible for microbial activity and is therefore regarded as the main source of energy for bacteria. Labile carbon has the ability to serve as a marker for various soil processes, including nutrient cycling, the production of soil aggregates, carbon sequestration (usually determined by changes in total organic carbon content), and the provision of habitat for biodiversity. This pool is more sensitive for changes in the management of organic manures and fertilization as compared to passive pool (recalcitrant carbon pool). Mazumdar *et al.* (2023) found that, by stimulating microbial activity, the INM, or addition of organics to soil, increases the labile carbon pools, which in turn permits higher C-decomposition rates. Additionally, they observed greater carbon dioxide evaluation decomposition in INM at 35°C, which was predominantly brought on by INM having more soil-labile C pools than other treatments. However, under INM, C-storage and sequestration were similarly higher. This review provides an unique opportunity to examine the effects of manure and fertilizer application on soil aggregation and aggregate associated carbon fractions and mineralization pattern of soil organic carbon in different size aggregate classes. Improved understanding of active and passive pools of soil carbon fractions will provide


Soil crumb consists of domains of oriented clays and quartz particles — Emerson (1959)

Microaggregate theory — Edwards and Bremner (1966)

Aggregate hierarchy theory — Tisdall and Oades (1982)

Postulation of microaggregate formation within macroaggregates — Oades (1984)

The soil organic matter that binds together microaggregates into macroaggregates is lost upon cultivation — Elliott (1986)

Four hierarchical pore categories form the mirror image for the aggregate hierarchy — Elliott and Coleman (1988)

Earthworm activity induces the formation of microaggregates within casts — Shipitalo and Protz (1989)

Porosity exclusion principle defines scale of effectiveness of binding agents — Dexter (1988); Kay (1990)

Aggregate hierarchy exists only in soils where organic matter is the major binding agent — Oades and Waters (1991)

Mechanisms involved in the formation, stabilization and degradation of microaggregates — Golchin et al. (1994a)

Corroboration of microaggregate formation within macroaggregates — Angers et al. (1997)

Disturbance increases macroaggregate turnover, which diminishes carbon stabilization in newly formed microaggregates within macroaggregates — Six et al. (1998)

Fig. 1 A time line of the critical advancements in the understanding of soil organic matter–aggregation interactions [Six *et al.,* 2004] valuable information for establishing sustainable fertilizer management systems to maintain and enhance soil quality.

Impact of FYM and fertilizer N on aggregate bound organic carbon

Soil organic carbon is one of the important aspect of soil (Yu *et al.,* 2017) which is regarded as the center of soil quality and its functions and a leading indicator of soil health (Zhao *et al.,* 2016). Soil organic carbon plays an important role in cycling plant nutrients, increasing grain yield and improving the physical, chemical properties of soils (Manna *et al.,* 2007). Fertilization as an agricultural management strategy is being used to promote soil carbon storage (Silveira *et al.,* 2013), which could directly or indirectly increase the soil organic carbon inputs and thereby change the availability of nutrients and soil turnover (Schmidt *et al.,* 2015). For instance, inorganic nitrogen fertilizer may indirectly enhance the soil organic carbon storage by increased crop residue input to soils (Tian *et al.,* 2015). Soil aggregates are the main storehouse of C sequestration. Soil aggregation is governed by many factors. Among them are texture, cation content in soils, clay mineralogy, aluminium and iron oxides, and SOM (Abiven *et al.,* 2009). Aggregation, on the other hand, also helps to stabilise soil organic C (SOC). Stable aggregates serve as markers of appropriate soil structure for SOC stabilisation and storage in addition to promoting healthy crop establishment and the physical environment of the soil in the root zone (Balesdent *et al.,* 2000). Soil aggregation is an intricate, hierarchical process which organises soil particles (Oades 1984; Tisdall and Oades, 1982). Persistent, transient, and temporary binding agents enable the formation of micro- and macroaggregates. According to their origin, soil aggregates can be divided into three groups: biogenic, physicogenic, and intermediate. Animal excrements, decaying plants, microbial exudates, and the compressive action of roots and fungal hyphae all contribute to the formation of biogenic aggregates (Pulleman *et al.,* 2005; Jouquet *et al.,* 2006) Physical soil compression, organo-mineral interactions, and other physical and chemical processes are examples of those that produce physicogenic aggregates (Pulleman *et al.,* 2005). The routes leading to intermediate aggregates are both physicochemical and biological. Mikha *et al.* (2015) revealed that aggregate associated carbon was significantly influenced by nitrogen treatment and depth. At the surface 0 to 5 cm depth, the amounts of carbon were associated with macro-aggregates (>1000, 250–500, and 53–250 µm) when different rates of fertilizer (F) were combined with manure (M) (0 + M, 90 kg ha^{-1} (N) nitrogen+ M, and 180 90 kg ha^{-1} N+ M) were significantly higher as compare with fertilizer or control treatments. The higher amounts of carbon were associated with macro-aggregates (500–1000 mm) when F rates were 90 and 180 kg N ha^{-1} compared with the control and combination of F + M treatments. Similar patterns for aggregate-associated carbon were observed at the 5 to 10 and 10 to 15cm depth and the value of soil organic carbon associated with microaggregates (53–250 mm) was approximately two times greater with the M and combination of F + M treatments compared with F alone and control treatments, whereas application of organic manure could influence soil organic carbon owing to the direct inputs of processed organic materials to soils (Ryals *et al.,* 2014). Application of organic fertilizers would result in a higher level of soil organic carbon than inorganic fertilizers (Xie *et al.,* 2014, Sun *et al.,* 2015). Trivedi *et al.* (2021) reported that among all the treatments, farm yard manure (FYM) + P’K’-treated plots contained highest soil organic carbon concentration within large macroaggregates which was 92 and 33% higher as compared to unfertilized control and NPK plots, respectively (Fig. 2). Among the minerally fertilized plots, large macroaggregates of NPK + L plots had 53% higher soil organic carbon concentration than unfertilized control plots. All manure-containing plots had higher soil organic carbon within large macroaggregates compared with NPK-treated plots. The soil organic carbon content inside small macroaggregates was also highest for FYM + P’K’ plots in surface soil layer followed by FYM + P’K’ + L plots. The amount of soil organic carbon in within microaggregate was significantly higher in FYM + P’K’ + L plots, which was 48 and 18% higher than control and NPK plots, respectively.

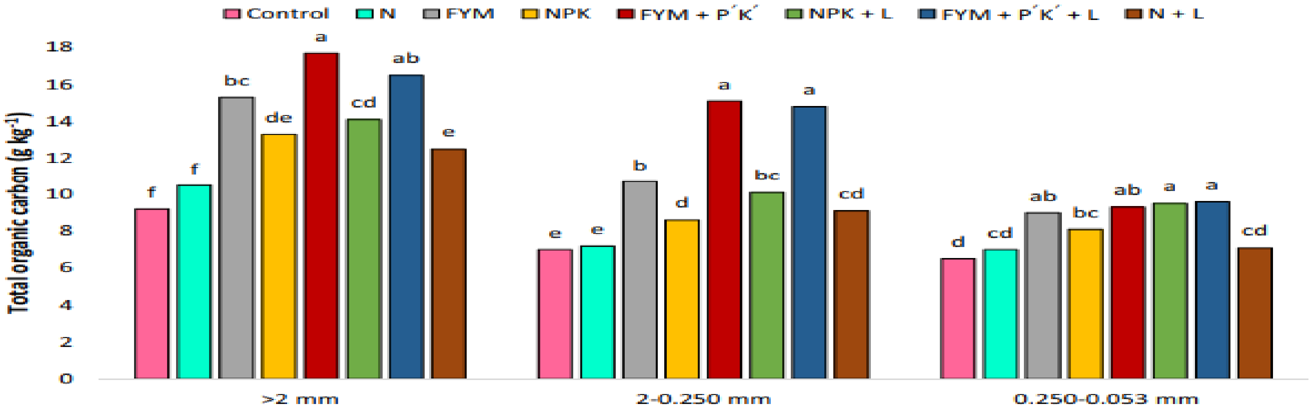


Fig.2: Total organic carbon concentration (g kg^{-1}) in soil aggregates as affected by 60 years of fertilization and liming under maize-wheat cropping system [Source: Trivedi *et al.,* 2021]

Naresh *et al.* (2015) reported that the highest soil organic carbon concentration was obtained in 0–5 cm depth and decreased with sub-surface depths for all treatments. Within treatments the highest soil organic carbon concentration of 5.8 g kg^{-1}in the surface layer (0–15 cm) of 100% organic as sole FYM treatment followed by 50% organic (FYM) + 50% recommended dose of fertilizer (RDF) (5.4 g kg^{-1}) treatment. All plots treated with organic amendments contained higher soil organic carbon in the surface and sub-soil compared with those not receiving any organics. The soil organic carbon concentration also improved with the application of 100% RDF (5.1 g kg^{-1}) and 50% RDF+50% RDF (foliar) (4.9 g kg^{-1}). In contrast, the soil organic carbon concentration increased with the application of organic materials even in the sub-soil. The mean profile soil organic carbon concentration increased from 2.2 g kg^{-1}in control to 4.4 g kg^{-1} in 100% organic as sole FYM. However, no increase in soil organic carbon concentration was observed in 50% RDF treatment. The combined application of inorganic and organic fertilizers and INM practices has been shown to improve soil organic carbon better than the simple addition of inorganic fertilizer (Sun *et al.,* 2015) Mazumdar *et al.* (2021) found that the INM treated plots retained the highest carbon content (Table.1) followed by inorganic fertilizer treatments and the control soil. The macroaggregate associated carbon (9.6 g kg^{-1}) was significantly higher in the INM treated plots as compare to all other treatments and microaggregates associated carbon (6.0 g kg^{-1}) also showed the similar trend as macroaggregates. The long-term application of FYM and inorganic fertilizer significantly increased the carbon concentration as compared to control in all the aggregate size fractions. Ghosh *et al.* (2018) observed that the significantly higher soil organic carbon content was found in plots with 50% NPK + 50% FYM followed by 50% NPK + 50% green manure (GM) in topsoil and the lower value of soil organic carbon was found within control plot. Aggregate associated soil organic carbon concentration significantly increased with aggregate size. The large and small macroaggregates consisted of higher amount of aggregate bound soil organic carbon as compared to microaggregates and silt + clay sized aggregates. Plots with 50% NPK + 50% GM had significantly highest aggregate-associated carbon in all size classes in both soil layers.

Table1: Carbon contents in four soil aggregate size fractions after 44 years of nutrient management practices [Source Mazumdar *et al.,* 2021]

Carbon content (g/kg of soil) in soil aggregates				
	Macroaggregates		Microaggregates	
Treatment/Soil aggregate fraction	Large Macro-aggregates (>2mm)	Small Macro-aggregates (<2mm)	Microaggregates (0.053-0.25mm)	Microaggregates+ silt fraction (<0.053mm)
Control	7.1d	6.4c	4.6c	7.50b
N	7.2d	6.4c	4.8bc	7.58b
NPK	7.8c	6.7bc	4.9bc	7.80b
INM	9.6a	8.1a	6.0a	9.11a

Some others factor like tillage practices and crop rotation also affect soil aggregation and ultimately soil organic carbon concentration. Conservation tillage generally increased soil organic carbon concentration of plow layer (Wang *et al.,* 2015), which is probably because conservation tillage can reduce soil disturbance, promote root development in the topsoil, and increase crop residue accumulation on the soil surface, thus enhancing soil aggregate stability (Mathew *et al.,* 2012). Mamta *et al.* (2023) studied the assessment of carbon pools and stability of soil aggregates in inceptisols of Indo-Gangetic plains as influenced by seven-year continuous tillage practices under maize-based cropping system and observed that the cropping system and tillage practices significantly affected organic carbon concentration. The total organic carbon concentration was significantly higher in permanent raised bed (8.62 g kg^{-1}) which was at par with zero tillage and the lowest total organic carbon concentration was recorded in control treatment (7.89 g kg^{-1}). In permanent raised bed treatments, total soil organic carbon concentration increased by 9.2% compared with control treatment. Among cropping system options, maize-chickpea had highest total organic carbon concentration (8.48 g kg^{-1}), which was also at par with maize-maize while maize-wheat cropping system recorded the lowest total organic carbon. There was 3.3% increase in total organic carbon concentration in maize-chickpea system over maize-wheat.

Effect of FYM and fertilizer N on aggregates bound organic carbon fractions

Soil organic carbon consists of various fractions varying in degree of decomposition, recalcitrance and turnover rates (Huang *et al.* 2008). The soil organic carbon fractions can be classified as labile, very labile, less labile and recalcitrant. These fractions exhibit different rates of biochemical and microbial degradation as well as different sensitivity to changes in different environmental conditions. Mamta *et.al* (2023) studied the effect of tillage-based practices and cropping system options on aggregates bound organic carbon fractions. Conservation-based practices like zero tillage and permanent raised bed showed increase in macroaggregates proportion, thereby enhanced aggregates bound organic carbon and its fractions with value as 26–30%, 27–32% and 26–27% higher very labile carbon, labile carbon and non-labile carbon respectively, over conventional tillage. Highest total soil organic carbon resided in the non-labile pool in all the treatments. The non-labile carbon (34% of total organic carbon) was the dominant carbon fraction, followed by very labile carbon (29%), less labile carbon (22%) and labile carbon (15%). On the other hand, the plots with maize-chickpea and maize-maize systems observed increased buildup of labile carbon pools and a higher proportion of labile carbon to total soil organic carbon among other maize-based cropping systems. However, non-labile carbon was found highest under maize-wheat cropping system.

Krishna *et al.* (2018) reported that the total organic carbon allocated into different pools (Table. 2) in order of very labile (VL) > less labile (LL) > non labile (NL) > labile (L), constituting about 41.4, 20.6, 19.3 and 18.7%, respectively. However, the contribution of VL, L and LL pools to soil organic carbon was 51.2, 23.1 and 25.5%, respectively. In comparison with control, the treatment in which application of farmyard manure (FYM-10 Mg FYM ha^{-1} season^{-1}) alone showed greater carbon 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%). With an increase in the dose of fertilization, on average, carbon allocation into passive pool was increased (33.0, 35.3, 40.7% and 39.3% of total organic carbon under control, 50% NPK, 100% NPK and 150% NPK treatments, respectively). In other hand, 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 carbon applied through FYM was stabilized as soil organic carbon. Trivedi *et al.* (2021) studied the effect of continuous application (for 60 years) of organic manure, fertilizer, and lime (L) alone or in combination on aggregate bound soil organic carbon and soil organic carbon fractions (Fig. 3) and found that the FYM + P’K’ plots had maximum amount of soil organic carbon inside large macroaggregates. Large macroaggregate of FYM + P’K’ had 11, 40, and 32% higher labile carbon compared with FYM, NPK, and unfertilized control plots, respectively. Similarly, large macro-aggregates of FYM + P’K’ plots had highest recalcitrant carbon, followed by FYM and mineral fertilized plots. Small macroaggregates

Table 2: Oxidizable organic carbon fractions (very labile, labile, less labile and non-labile) in soils (g kg^{-1}) at different layers (cm) under different treatments [Source: Krishna *et al.,* 2018]

Treatment	Very labile carbon				Labile carbon				Less labile carbon				Non labile carbon			
	0-5	15-30	30-45	Total	0-5	15-30	30-45	Total	0-5	15-30	30-45	Total	0-5	15-30	30-45	Total
Control	3.6±0.5c	1.4±0.3b	1.3±0.2a	6.3±0.4b	2.4±0.3a	1.0±0.2a	0.8±0.4a	4.2±0.6a	1.5±0.3c	0.6±0.4c	0.4±0.0c	2.6±0.7d	1.2±0.5b	1.2±0.3a	1.2±0.2b	2.6±0.5b
50% NPK	4.6±0.3bc	2.1±0.7ab	1.5±0.1a	8.1±0.9a	1.7±0.4ab	0.9±0.5a	0.7±0.2a	3.3±0.7a	1.8±0.1c	0.4±0.1c	0.5±0.2c	2.7±0.1cd	1.2±0.9b	1.7±0.8a	0.7±0.4ab	3.5±1.8ab
100% NPK	4.4±0.3bc	2.3±0.2a	1.4±0.5a	8.0±0.7a	1.8±0.4ab	0.8±0.5a	0.6±0.3a	3.2±0.8a	2.5±0.3ab	0.8±0.1bc	1.1±0.2ab	4.4±0.1b	1.3±0.6b	1.5±0.6a	0.5±0.2ab	3.3±1.0ab
150% NPK	5.0±0.2ab	2.6±0.2a	1.5±0.1a	9.0±0.3a	1.2±0.3b	0.7±0.2a	0.9±0.2a	2.8±0.4a	2.6±0.2a	0.9±0.1bc	0.4±0.2c	3.9±0.1b	1.4±0.3b	1.5±0.2a	0.8±0.1a	3.7±0.3ab
100% NPK+FYM	4.8±0.2ab	2.0±0.2a	1.3±0.3a	8.1±0.2a	1.9±0.3ab	0.7±0.2a	0.7±0.3a	3.4±0.2a	2.7±0.6a	1.5±0.2a	1.4±0.1a	5.6±0.7a	2.0±0.8b	1.3±0.1a	0.3±0.3ab	3.5±0.7ab
FYM	5.9±1.3a	2.2±0.2a	1.4±0.3a	9.5±1.6a	2.5±0.9a	0.7±0.3a	0.7±0.2a	3.9±0.9a	1.9±0.7bc	1.7±0.2a	1.0±0.2b	4.5±0.7ab	3.7±1.3a	1.0±0.2a	0.5±0.5ab	5.1±1.9a
Fallow	4.2±0.7bc	1.5±0.5b	0.7±0.3b	6.3±0.8b	2.2±1.0ab	1.0±0.3a	1.0±0.4a	4.1±1.1a	1.5±0.3c	1.3±0.7ab	0.9±0.4b	3.8±1.2bc	2.1±0.2b	1.4±0.7a	3.9±0.9ab	0.4±0.2ab

±Standard error; Different small letters within columns indicate significance at p<0.05

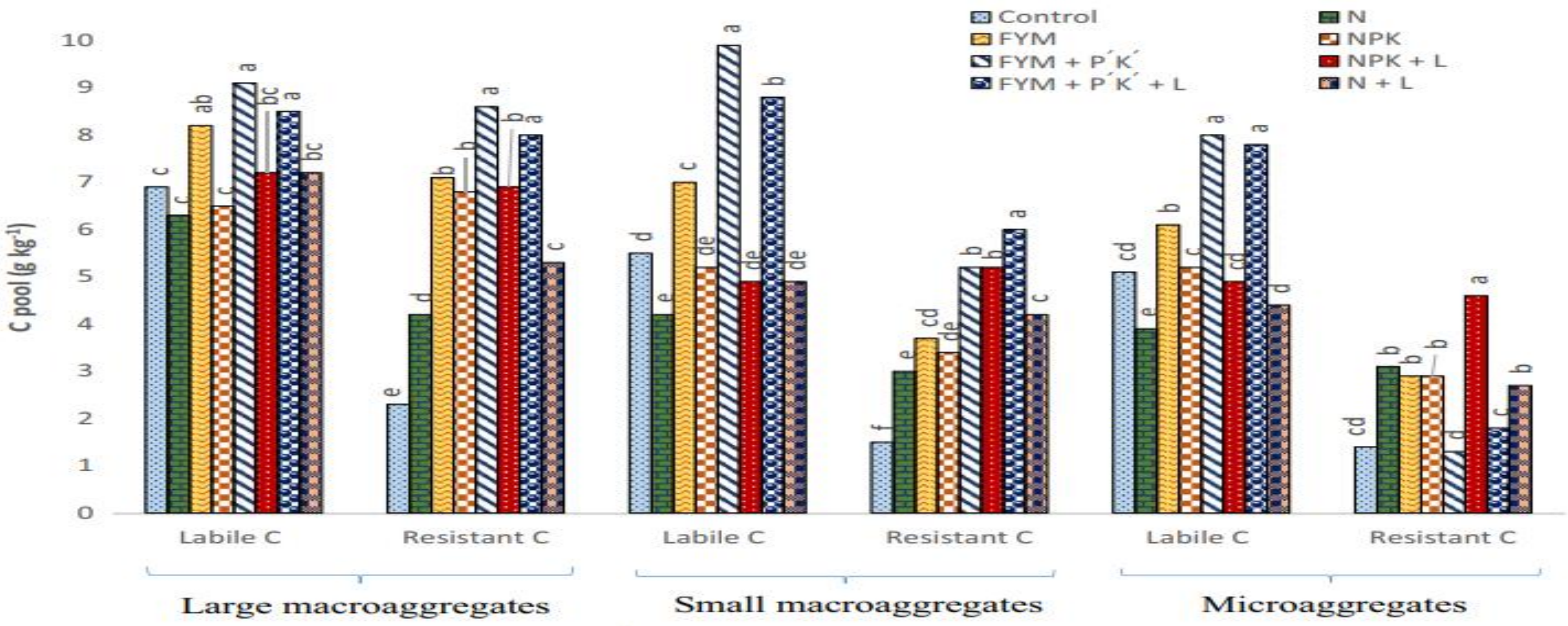


Fig. 3: Labile and resistant soil carbon pools (g kg^{-1}) in soil aggregate fractions as affected by 60 years of fertilization and liming under maize-wheat cropping system in an Alfisol [Source: Trivedi *et al.,* 2021

of FYM + P’K’ plots contained 80, 90, 41, and 12% higher labile carbon than the small macroaggregates of unfertilized control, NPK, FYM, and FYM + P’K’ + L plots, respectively. But unlike labile carbon, small macroaggregates of FYM + P’K’ + L had 15% more recalcitrant carbon than FYM + P’K’ plots. Labile carbon within microaggregates was similar for unfertilized control and NPK plots and was least for plots treated with nitrogen fertilizer alone. Recalcitrant carbon inside microaggregates was maximum for NPK + L plots, followed by nitrogen plots.

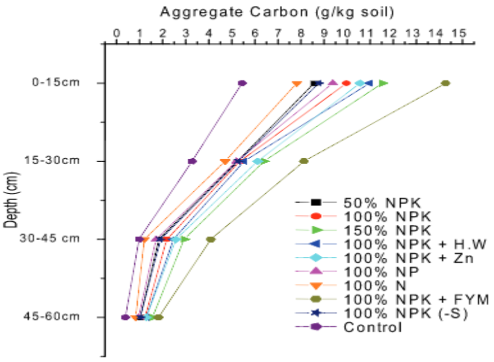


Fig. 4: Effect of organic and inorganic fertilizers on aggregate carbon (g kg^{-1} soil) after rice harvesting [Source: Pant *et al.,* 2021]

Pant *et al.* (2021) found that soil organic carbon along with its pools were affected by the long-term use of fertilizer in a fixed rice-wheat crop sequence. The combination of this integrated application of (100% NPK + 15 t ha FYM^{-1}) significantly built organic carbon fractions like total organic carbon, microbial biomass carbon (MBC), particulate organic carbon (POC), aggregate bound organic carbon at all soil depths. Maximum POC content was obtained in soil at all depths where 100% NPK was applied along with FYM followed by 150% NPK. At 0–15 cm, POC content under 100% NPK+FYM and 150% NPK treatments over control were 551% and 405% higher after rice harvest (Fig. 4) and 445% and 210% higher after wheat harvest (Fig. 5) respectively. Continuous application of NPK with FYM in rice-wheat system resulted in significantly higher POC over control at 0–15 cm soil depth. The maximum aggregate carbon concentration in soil at all depths was obtained under plots where, 100% NPK was applied along with FYM followed by 150% NPK treatments. However, there was subsequent decrease in aggregate carbon concentration with increase in depth. The treatment 100% NPK with FYM at 0–15 cm depth recorded 683% increment of aggregates bound organic carbon over 45–60 cm after rice harvest whereas at the same depth, it was about 612% increase over 45–60 cm after wheat harvest. The integrated approach of nutrient management showed positive impact on soil microbial biomass carbon and received more biomass carbon in surface layers with subsequent decrease with increase in depth.

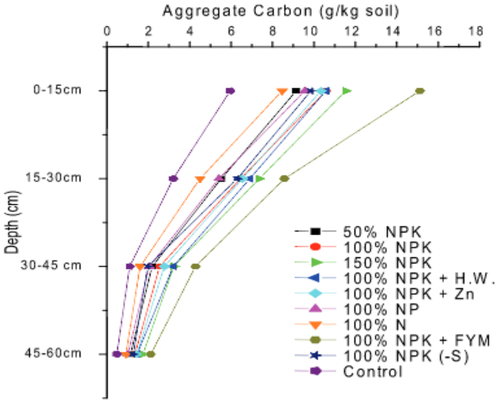


Fig.5: Effect of organic and inorganic fertilizers on aggregate carbon (g kg^{-1} soil) after wheat harvesting. [Source: Pant *et al.,* 2021]

Effect of FYM and fertilizer N on mineralization pattern of soil organic carbon

Mineralization in soil is the decomposition (*i.e.,* oxidation) of the chemical compounds in organic matter, by which the nutrients in those compounds are released in soluble inorganic forms that may be available to plants (Beare *et al.,* 1994). Thus, evaluating soil organic carbon mineralization and stabilization in aggregates is key to understand the mechanisms of long-term soil organic carbon-dynamics in soil (Rabbi *et al.,* 2014). Li *et al.* (2018) studied the response of soil organic carbon fractions, microbial community composition and carbon mineralization to high-input fertilizer practices under an intensive agricultural system and observed that the cumulative CO_2-C emission over time tended to be higher in mineral N and P fertilizers in combination with both maize straw and chicken manure and mineral N and P fertilizers in combination with maize straw than in unfertilized control and inorganic N and P fertilizers treatments throughout the incubation period. By the end of the incubation, the mineral N and P fertilizers in combination with both maize straw and chicken manure treatment had largest increase of the cumulative mineralization carbon by 85%, and the mineral N and P fertilizers in combination with maize straw treatment also resulted in an increase of 53% of cumulative mineralization compared to unfertilized control. Moreover, compared to unfertilized control, the mineral N and P fertilizers in combination with both maize straw and chicken manure and mineral N and P fertilizers in combination with maize straw treatments enlarged the size of the easily mineralizable carbon pool by 103 and 78%, respectively. Dou *et al.* (2008) reported that mineralized carbon was significantly greater under no-till than conventional tillage at 0 to 30 cm, except for continuous wheat treatment where no difference was observed. At 0 to 5 cm, mineralized carbon was 27, 34, and 42% greater for continuous wheat-soybean–wheat–sorghum rotation, and double-cropped wheat–soybean, respectively, under no-till than under conventional tillage. Similar results were observed for the 15 to 30 cm depth. At the 5 to 15 cm depth, however, mineralized carbon was greater under conventional tillage than no-till.

Table 3: Carbon mineralized in differentially amended soils

Soil type	Cumulative Carbon mineralized	References
Alluvial sediments	85% of carbon is mineralized under high fertility conditions (Inorganic fertilizer along with organic manure)	Li *et al.,* 2018
Ultisols	Highest amount of carbon mineralized under organic manure amended treatment	Wang *et al.,* 2020
Tertiary basalt	Highest amount of carbon mineralized under natural pasture land	Rabbi *et al.,* 2014
Alfisols	Highest amount of carbon mineralized under chicken manure along with biochar amended soil	Li *et al.,* 2022

Cropping intensity had less effect on mineralized carbon than tillage. The greatest difference in mineralized carbon between conventional tillage and no-till, was observed at the 0 to 5 cm depth, where no-till increased mineralization by 35% compared with conventional tillage. Mineralized carbon as a fraction of soil organic carbon, however, was greater at 0 to 15 cm for conventional tillage than no-till. This fraction ranged from 1.9 to 3.1% for conventional tillage and from 1.6 to 2.7% for no-till. Wang *et al.* (2021) studied the effect of organic amendments on carbon mineralization in different aggregate size classes and observed that the soil organic carbon concentration in all aggregate fractions was significantly affected by the fertilizer treatments and followed the order as no fertilization < inorganic NPK fertilizer < NPK + straw < NPK + straw and manure. Similar to the soil organic carbon concentration, the potential carbon mineralization rate in all aggregates was significantly increased by the organic amendments, and NPK + straw and manure had a greater impact than NPK + straw NS. Among the aggregate fractions, the highest soil organic carbon concentration and carbon mineralization rate were observed in <250 μm aggregates, followed by 250–2000 μm aggregates and >2000 *μm* ag-gregates. Zhang *et al.* (2023) investigated the effects of nitrogen addition and aggregate fractions on cumulative carbon mineralization and conclude that nitrogen addition significantly increased cumulative carbon mineralization within aggregate fractions, with micro-aggregates showing the highest and silt-clay fraction showing the lowest levels (Fig. 7). Among the various nitrogen treatments, the treatment in which application of 180 kg N ha^{-1} had a higher cumulative carbon mineralization rate than the application of 360 kg N ha^{-1}. Bimuller *et al.* (2016) conducted a long-term (224-days) laboratory incubation experiment and reported the cumulative carbon mineralization rates, the fine aggregates (< 2mm) emitted more CO2–C per mass soil and less CO2–C per unit mass soil organic carbon than the other size classes (Fig. 8). After 224 days, all size classes had mineralized only around 4% of their soil organic carbon. The cumulative CO2–C mineralization per unit mass soil organic carbon significantly differed between the fine aggregates and the other size classes after 224 days.

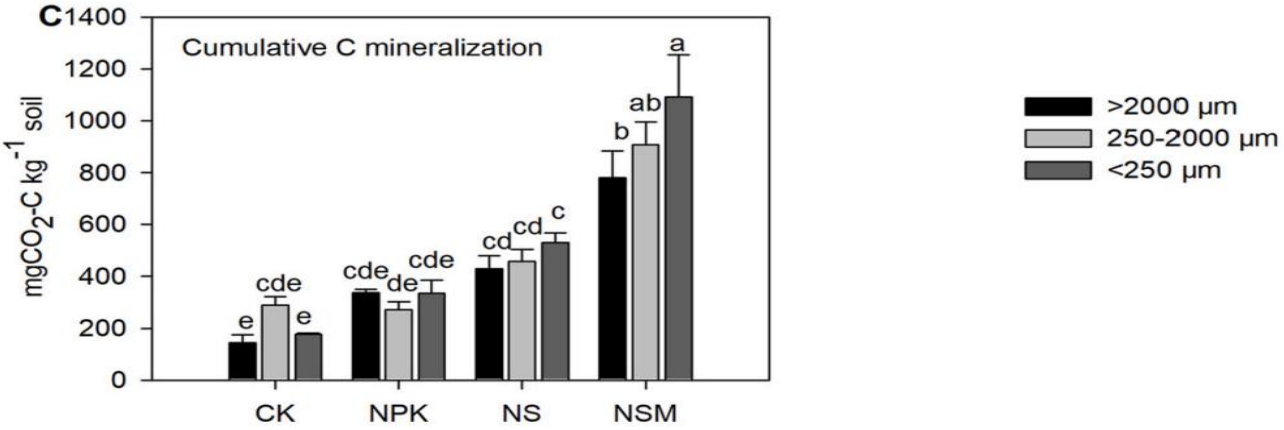


Fig 6: Effects of the fertilization treatments and aggregate size on the cumulative carbon mineralization [Source: Wang *et al.,* 2021

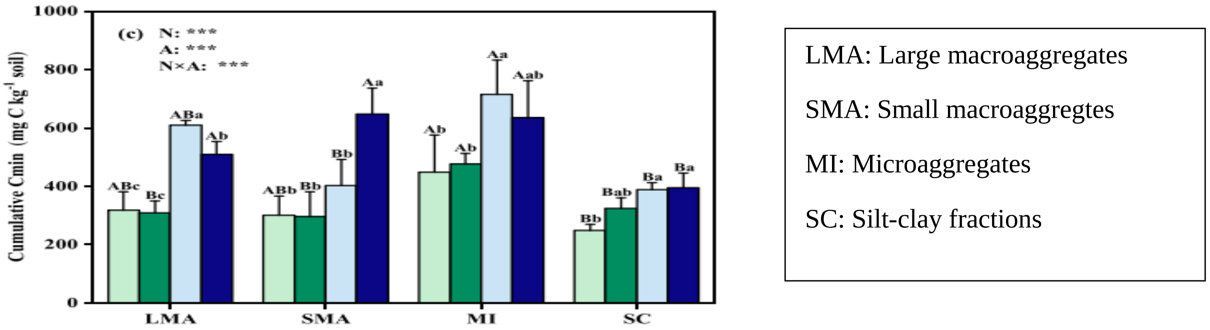


Fig 7: Effect of nitrogen addition and aggregate fractions on the cumulative carbon mineralization [Source: Zhang *et al.,* 2023]

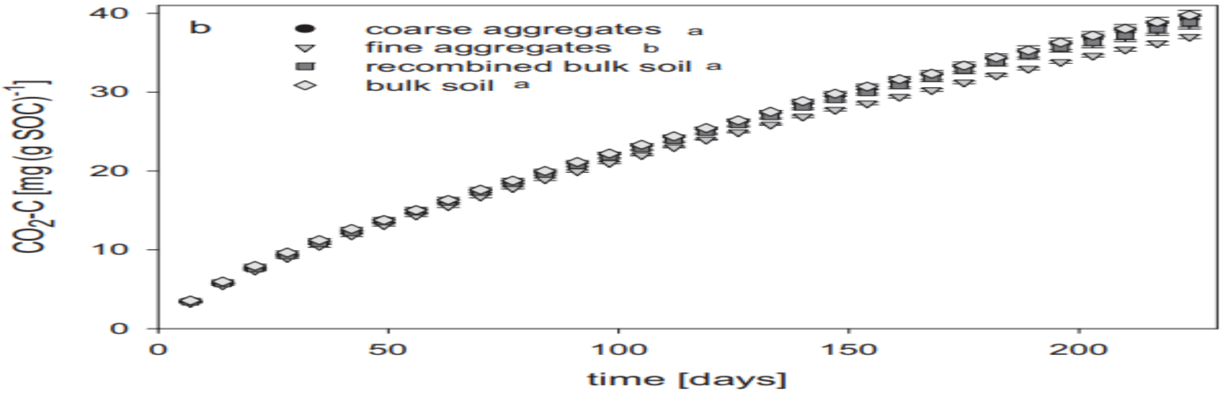


Fig 8: Cumulative CO2–C concentrations in mgg^{-1} soil organic carbon of three incubated size classes [Source: Bimuller *et al.,* 2016]

Conclusion

This review study concludes, that the applications of FYM and fertilizer nitrogen significantly influence the aggregate bound organic carbon content, their fractions and cumulative carbon mineralization. Compared to no fertilization and solely inorganic fertilizer application, fertilization with inclusion of organic manure preserved greater organic carbon content. Soil organic carbon significantly increases with increasing the size of the aggregates. In comparison to micro-aggregates and silt + clay sized aggregates, the large and small macro-aggregates had a larger quantity of aggregate bound soil organic carbon. Additionally, the treatments with mixed applications of manure, straw, and mineral fertilizers showed the higher increase in aggregate bound organic carbon. It has been demonstrated that the combined application of inorganic and organic fertilizers and INM practices has been shown to improve soil organic carbon better than the simple addition of inorganic fertilizer. The amount of aggregate bound soil organic carbon varies with depth; for all treatments, the maximum soil organic carbon concentration was found in the first 0–5 cm of soil. The organic additions and fertilization considerably improved the potential rate of carbon mineralization in all aggregates. The aggregate fractions with the greatest soil organic carbon mineralization rate were those with a diameter of less than 250 mm, followed by those with a diameter of 250 mm to more than 2000 mm. Labile fractions of organic carbon was found higher in macroaggregates and recalcitrant organic carbon fractions was found higher in microaggregates. Thus, soil aggregates was influenced by long term addition of organic manures and fertilization and higher carbon mineralization and labile carbon fractions was reported in macroaggregates compared to microaggregates.

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