

Original Research Article

Impact of Long-Term Nutrient Management on Carbon Dynamics under Cluster bean-Wheat cropping System in Western Rajasthan

Abstract

A field experiment was started in 2008 under All India Co-ordinated Research Project- Soil Test Crop Response in western Rajasthan to study the long-term effects of nutrient management strategy using Soil Test Crop Response (STCR) approach on cluster bean– wheat cropping system. The present investigation indicated effects of organic compost and inorganic fertilizer as per soil test crop response approach basis on soil carbon dynamics. The treatments consisted of general recommended dose, target yield 15 q ha⁻¹, target yield 15 q ha⁻¹ with Integrated Plant Nutrient System, target yield 20 q ha⁻¹ and target yield 20 q ha⁻¹ with Integrated Plant Nutrient System. The soil organic pools were studied after 9 years and it was found that the total C and its different pools of soil increased significantly under target yield 20 q ha⁻¹ with Integrated Plant Nutrient System. Active and passive pools of carbon of soil increased significantly under target yield 20 q ha⁻¹ with Integrated Plant Nutrient System as compared to the target yield 15 and 20 q ha⁻¹ treatments without IPNS and at par with target yield 15 q ha⁻¹ with Integrated Plant Nutrient System. Carbon management index and carbon stock increased significantly under target yield 20 q ha⁻¹ with Integrated Plant Nutrient System. It can be concluded that combined application of organic and inorganic nutrient in long term basis significantly enhance carbon sequestration rate, consequently soil quality.

Key word: STCR, Carbon fractions, Carbon management index, long-term fertilization,

1. Introduction

Soil organic carbon, the major component of soil organic matter, is important in all soil processes. The term "Soil Organic Matter" embraces the non-mineral fractions of soil is essentially derived from residual plant and animal material, synthesized and decomposed by microbes under the influence of temperature, moisture and ambient soil conditions. It plays an

important role in maintaining soil quality and eco-system functionality (Das et al. 2016; Das et al. 2018; Datta et al. 2018). Land use and agricultural practices such as tillage, irrigation and fertilization, all influence the storage of SOC (Ghosh et al. 2018; Ghosh et al. 2021; Jat et al. 2019; Mandal et al. 2020; Nath et al. 2018). It is a direct source of plant nutrient elements, the release of which depends upon microbial activity by affecting the cation exchange capacity, organic matter is directly involved in availability of nutrient elements (Brar et al. 2013; Chatterjee et al. 2018).

Soil organic carbon (SOC) is a very crucial element in soil fertility and productivity (Benbi, 2015; Singh and Benbi, 2018). It is found in the soil in the forms of labile and non-labile (Juhi et al., 2022). Addition of crop residue in soil significantly enhanced soil carbon content (Kharia et al., 2017). The labile form contains three fractions that are frac1 (very labile carbon), frac2 (labile carbon) and frac3 (less labile carbon), and frac4 of the carbon is non-labile (Benbi et al. 2015; Benbi et al. 2017). These forms of carbon help in maintaining soil health (Naik et al. 2016; Bhattacharyya et al., 2013; Parihar et al., 2018b; Tian et al., 2015). The labile C pool belongs to SOC with rapid turnover rates, which serves as an energy source for soil food webs, and therefore increases nutrient cycling, quality and productivity of soil (Chan et al. 2001; Chen et al. 2017; Bharali et al., 2017). It is very crucial in long-term carbon storage (Jiang et al. 2014; Ahirwal et al., 2021). Labile Carbon pool determined by chemical-extraction techniques is considered an early indicator of management induced change in quality and composition of soil organic matter (Benbi and Senapati, 2010). Walkley and Black (1934) offered a method for measuring the C content of soil and Chan et al. (2001) improved the Walkley-Black method to divide SOC into four fractions with different labilities and oxidizabilities which are very labile carbon (C_{VLC}), labile carbon (C_{LC}), less labile carbon (C_{LLC}), and recalcitrant carbon or non-labile carbon (C_{NLC}). The VLC and LC fractions are the most readily Oxidizable fractions and mainly composed of polysaccharides, decaying young organic matter, fungal hyphae, and other microbial products, which contribute to the formation of macro aggregates and availability of nutrients (Maia et al. 2007). The LLC and NLC fractions are related to compounds of high chemical stability and are slowly decomposed by soil microbe (Sherrod et al. 2005). The pool being readily accessible to microorganisms directly impact plant nutrient supply (Hossain et al., 2017; Saha et al. 2021). This pool is also sensitive to land management changes. The highly recalcitrant or passive pool is on the other hand, changed only very slowly by microbial activities

and hence hardly serves as a good indicator for assessing soil quality and productivity (Majumdar et al. 2007; Benbi et al. 2018; Parihar et al., 2018a). Some of the important labile pools of SOC currently used as indicators of soil quality are microbial biomass C, mineralizable C, oxidizable organic C fractions and light-fraction. The vertical distribution of Soil Organic Carbon (SOC) in the soil profile is, though unclear. In the subsoil below 30cm depth, Soil Organic Carbon (SOC) stocks fluxes are critical for the soil functions. Aside from strong soil inorganic carbon and Soil Organic Carbon (SOC), the subsoil contributes to the cycling of elements with the consequence, e.g. plant nutrients (Paul et al., 2019; Ramesh et al., 2015; Sahoo et al., 2019). Despite lesser concentration, the subsoil is probable also an important factor for the long-term storage of SOC, as the radiocarbon age and turnover time of OM increased with a decreased in soil depth. Thus, the Organic Matter in the subsoil can impact the mitigation of atmospheric increases in CO₂ by SOC sequestration (Lorenz and Lal, 2016).

This method could be applied for finding out different subfractions of soil organic matter *i.e.* very labile (C_{VLC}), labile carbon (C_{LC}), less labile carbon (C_{LLC}) and non-labile carbon (C_{NLC}) may help to understand the soil quality and health in terms of their capacity to store active and passive pools of soil organic matter.

2. Materials and Methods

A field experiment was started in 2008 under All India Co-ordinated Research Project- Soil Test Crop Response in western Rajasthan to study the long-term effects of nutrient management strategy using Soil Test Crop Response approach on cluster bean- wheat cropping system. The present investigation indicated effects of organic compost and inorganic fertilizer as per soil test crop response approach basis on soil carbon dynamics. After 11 years (2018), soil samples were collected from experimental field in Agroclimatic zone Ic (Hyper arid partially irrigated western plain) of Rajasthan comprising canal irrigated North-Western plains of Bikaner located between 28°10' N latitude, 73°18' E longitude. The climate is characterized as hyper arid with monsoonal influence. Annual bimodal rainfall ranges between 220 and 230 mm. The maximum and minimum temperature ranged between 35°C to 39.5°C and 16.7°C to 26.9°C during crop growing season. July–October).

The experiment was laid out in a Randomized Block Design with five treatment combinations and four replications. Details of treatments with their symbol given in table 1. In

this experiment on treatment is general recommended dose and in the pair treatments same target yield but nutrient applied with or without IPNS according to STCR recommended equation.

These requirements were calculated following the equation

$$\text{For Nitrogen (T}_2 \text{ and T}_4) = 6.70 T^* - 0.37 N^{**}$$

$$\text{For Nitrogen (T}_3 \text{ and T}_5) = 6.70 T^* - 0.37 N^{**} - 0.65 O^{***}N$$

$$\text{For Phosphorus (T}_2 \text{ and T}_4) = 9.90 T^* - 2.15 P_2O_5^{**}$$

$$\text{For Phosphorus (T}_3 \text{ and T}_5) = 9.90 T^* - 2.15 P_2O_5^{**} - 2.05 \times 50 O^{***} P_2O_5$$

$$\text{For potassium (T}_2 \text{ and T}_4) = 6.78 T^* - 0.23 K_2O^{**}$$

$$\text{For potassium (T}_3 \text{ and T}_5) = 6.78 T^* - 0.23 K_2O^{**} - 0.62 O^{***} K_2O$$

*target yield ** amount of available nutrient present in soil ***Nutrient % in compost

Organic compost- Treatments with IPNS, nutrient applied as per the prescription based nutrient recommendation Kg compost plot⁻¹. Chemical composition of compost was nitrogen (0.68 %), phosphorus (0.35 %) and potassium (0.62 %)

Fertilizer application

Urea as nitrogen source, single super phosphate for phosphorus and muriate of potash for potassium were applied in different treatments.

Table 1 Details of treatments with their symbols

Treatment symbols	Treatment details
T ₁ -General recommended dose	General recommended dose : (20 Kg Nitrogen ha ⁻¹ 32 Kg P ₂ O ₅ ha ⁻¹)
T ₂ -Target yield 15 q ha ⁻¹	: Soil test crop response recommendation dose for target 15 q ha ⁻¹
T ₃ -Target yield 15 q ha ⁻¹ with IPNS	: Soil test crop response recommendation under integrated plant nutrient system dose for target 15 q ha ⁻¹
T ₄ -Target yield 20 q ha ⁻¹	: Soil test crop response recommendation dose for target 20 q ha ⁻¹
T ₅ -Target yield 20 q ha ⁻¹ with IPNS	: Soil test crop response recommendation under integrated plant nutrient system dose for target 20 q ha ⁻¹

Soil Sampling - Soil samples from each treatment plot taken with the help soil samples were taken with a soil core sampler (inner diameter 7 cm) by boring randomly at four places after the harvest of the crop at 0-7.5 and 7.5-15 cm soil depths. Collected soil samples were air dried, ground in wooden pestle and mortar, passed through 2 mm sieve and preserved in cloth bags for the subsequent analysis for different chemical properties. The soil samples from each replicate subplot were brought back to the laboratory, immediately sieved through a 2-mm sieve and

stored at 4⁰C until used for the various tests. Total organic carbon – A wet oxidation diffusion procedure was used to determine total organic carbon in the soil sample (Snyder and Trofymow, 1984). Permanganate Oxidizable Carbon- The permanganate-oxidizable organic carbon (PmOC) was determined following the procedure of Tirol-Padre and Ladha (2004). Different soil organic carbon pools- The content of oxidizable organic carbon and its different fractions in the soil were determined following the Walkley and Black (1934) method as modified by Chan et al. (2001) using 5, 10 and 20 ml of concentrated (18.0 mol l⁻¹) H₂SO₄ and K₂Cr₂O₇ solution. This resulted in three acid-aqueous solution ratios of 0.5:1, 1:1 and 2:1 that corresponded to 6.0, 9.0 and 12.0 mol L⁻¹ H₂SO₄, respectively, and produced different amounts of heat of reaction to bring about oxidation of SOC of varying oxidizability. The amounts of oxidizable organic carbon thus determined allowed separation of TOC into the following four fractions of decreasing oxidizability as defined by Chan et al. (2001):

Pool I	Very labile (C _{VL})	Organic carbon oxidised by 12 N H ₂ SO ₄
Pool II	labile carbon (C _L)	Difference in carbon oxidised between 18 N and that 12 N H ₂ SO ₄ (18 N – 12 N H ₂ SO ₄)
Pool III	less labile (C _{LL})	Difference in carbon oxidised between 24 N and 18 N H ₂ SO ₄
Pool IV	Recalcitrant (C _{RC})	Difference in organic C extracted with 24 N H ₂ SO ₄ and TOC determined by CHN analyzer (TOC–24 N H ₂ SO ₄).

Active pool (AP) and passive pool (PP) of organic carbon - Active pool of organic carbon was computed by adding fraction I and fraction II, whereas, passive pool of organic carbon was determined as addition of fraction 3 and fraction 4. Active pool of organic carbon represents amount of organic carbon present in easily oxidisable form in soil. Whereas, passive pool of organic carbon is resistant to decomposition, thus, it has higher mean residence time in soil. Hence, from soil carbon sequestration point of view storing more carbon in passive pool is important.

Soil organic carbon and soil organic carbon stocks - SOC content was determined using the rapid titration method (wet combustion method) as described by Walkley and Black (1934). The soil carbon stocks were calculated from the SOC content measured at different depth intervals by multiplying them with the respective bulk density and the thickness of the corresponding soil layer; and expressed as Mg ha⁻¹. Soil carbon management index-The CMI was calculated based on the method of (Blair, Lefroy, and Lisle, 1995). The CMI = CPI× LI× 100.The CPI was

determined as follows: $CPI = (\text{Total organic C content in sample soil}) / (\text{Total organic C content in reference soil})$. The liability index (LI) was calculated as follows: $LI = (\text{labiality of C in sample soil}) / (\text{labiality of C in reference soil})$. Statistical analysis By using SPSS (Statistical Package for the Social Science), software developed by three PhD students at the University of Stanford (Norman H. Nie, C. Hadlai (Tex) Hull and Dale H. Bent), after graduation N.

3. Results and Discussion

3.1. Organic carbon fractions of different degree of oxidisability

Data showed that long term nutrient management strategies through IPNS and without IPNS organic carbon fractions at 0-7.5 cm and 7.5-15 cm soil depths have been presented in table 1. Comparatively higher proportions of different oxidisable fractions were found in top 0 - 7.5 cm soil and decrease with increase depth. The magnitudes follow the order total organic carbon > recalcitrant carbon > less labile carbon > very labile carbon > labile carbon > permanganate oxidizable. It's ranging from 1.92 to 3.67, 1.01 to 1.70, 0.449 to 0.901, 0.289 to 0.673, 0.121 to 0.418 and 0.112 to 0.295 g C kg⁻¹, total organic carbon, recalcitrant carbon, less labile carbon, very labile carbon, labile carbon and permanganate oxidizable respectively. Significant variation was also obtained in active pool (AP) and passive pool (PP) under different treatments. Highest AP and PP SOC were recorded in 0-7.5 soil depth under the treatment target yield 20 q ha⁻¹ with IPNS *i.e.*, AP SOC 1.09 g C kg⁻¹ and PP SOC 2.60 g C kg⁻¹, similarly at 7.5-15 cm soil depth AP and PP SOC were recorded as 0.578 and 1.943, respectively under the treatment target yield 20 q ha⁻¹ with IPNS. The close relationships between the various labile organic C fractions present in soil suggested that pathways between these different organic C fractions exist, which makes them interdependent. Manuring enhanced PmOC content in soils due to the presence of higher root exudates, which contained lingo-cellulose residues (Arshad et al., 1990; Bhattacharyya et al., 2012). Decreased PmOC with increased soil depth might be due to slow and low translocation of leaf litter and applied compost. The increased labile C content with application of nutrient thorough with and with IPNS system could be because of the priming effect of applied nutrients on fresh organic materials in the soils. All these amendments stimulate the microbial activity helping SOC decomposition due to rapid excretion of the labile C (Yagi et al., 2005). The rise in recalcitrant C in target yield 20 q ha⁻¹ with IPNS plots could be related to resistance induced by biochemical property of organic compounds present either in

organic material or plant materials (McLauchlan et al., 2006; Yan et al., 2012). Studies showed that compost application increased lignin and lignin-like products, the main constituents of resistant C pools (Paul et al. 1996; Rovira and Vallejo, 2002; Belay-Tedla et al. 2009). Besides higher organics inputs, the greater amounts of recalcitrant C under target yield 20 q ha⁻¹ with IPNS than same yield target without without IPNS might be due to increased decomposition of labile compounds and accumulation of recalcitrant materials over time with target yield 20 q ha⁻¹ with IPNS (Lopez-Capel et al. 2008).

3.2. Soil carbon management index

As C_{poc} provides useful information on the nature and turn-over rate of different organic carbon pools, carbon management index (CMI) was computed. Results indicate that CMI was significantly varied under different treatments in 0-7.5 cm and 7.5- 15 cm soil depth. It is ranged from 92.27 % to 129.2 % (Table 2). Highest CMI recorded under treatment yield 20 q ha⁻¹ with integrated plant nutrient system *i.e.*, 129.2% which is 29.2% more than general recommended dose, 35.13% more in same target yield without integrated plant nutrient system at 0-7.5 cm soil depth which is at par with target yield 15 q ha⁻¹ with integrated plant nutrient system. At second depth *i.e.*, 7.5-15 cm soil depth not influenced significantly carbon management index. The CMI provides an indication of changes in the C dynamics of soil systems, which has been used to assess the capacity of management practices to promote soil quality (Kalambukattu et al., 2013). Blair et al. (1995) reported that the actual CMI values were not important, but the differences reflect how different management practices impacted reference. In the present study, the CMI in soils at the two different depths (0–7.5 cm, and 7.5-15 cm) that received nutrient through IPNS showed higher CMI than without IPNS treatments. The result is in agreement with Blair et al. (2006) who reported that farmyard manure with chemical fertilizer significantly increased CMI compared with any other chemical fertilizer treatments in a long-term experiment started from 1843. The reason might be that the increase in annual C addition and the changes in organic matter quality, thus modifying the lability of C to KMnO₄ oxidation (Tirol-Padre and Ladha, 2004). In the present study, only compost additions significantly increased CMI in the 0–7.5 cm and 7.5-15 cm the reason may be that the larger amount of C entered into the soil from decomposed compost and increased the lability of C in cluster bean soils (Gong et al., 2009). The CMI were higher in target yield 20 q ha⁻¹ with IPNS treatment than that without IPNS treatment at 0–7.5 cm depth may be due to the decrease of labile carbon which to increase in the

recalcitrant fraction of C in the surface layer (Ghosh et al., 2012). But there was no significant difference ($p > 0.05$) in CMI 7.5-15 cm soil depth. The reason may be that it was strongly related to root C inputs, crop residues, and application of chemical fertilizer with soil tillage which often accumulated in the deep layer, higher residue recycling and other biological activities in these soil layers (Chaudhary et al., 2017). In addition, the CMI was correlated with soil bulk density in our study. These results reinforced the suitability of using labile C for calculating the CMI and the CMI as a reliable index to assess the quality of soil management systems. The higher CMI of soil in compost return treatments than that of in without IPNS alone and with IPNS input treatments fit with our Hypothesis 2 that soil carbon management index would be higher in nutrient management through IPNS than that of in without IPNS condition.

3.3. Soil organic carbon stock

Long term nutrient management strategies through integrated plant nutrient system and without integrated plant nutrient system were significantly influenced organic carbon stock in different depths in soil. Carbon stock varied from 16.08 Mg c ha⁻¹ to 29.58 Mg c ha⁻¹ in 0-7.5 cm and 7.5- 15 cm soil depth. Highest soil carbon stock 29.58 Mg c ha⁻¹ and 23.68 Mg c ha⁻¹ at 0.7.5 cm and 7.5-15 cm soil depths, respectively) was found under target yield 20 q ha⁻¹ with integrated plant nutrient system treatment. It has been widely accepted that various management practices could increase the SOC content (Moharana et al., 2012; Wang et al., 2014). The content of SOC is determined by the balance between C inputs and decomposition losses (Lal, 2008). Consistent with our Hypothesis 1 that SOC content were increased under organic manure condition, the result showed that application of organic materials application generally increased organic carbon content in the different soil depths (0–7.5 cm, and 7.5-15 cm) as compared to the without IPNS, with the effectiveness being highest with organic manure additions was probably due to its lowest C/N ratio and organic manure fast decomposition (Gong et al. 2009), and thus causing greater potential for SOC sequestration and accumulation of carbon (Gami et al. 2009). In the present study, the SOC in 0–7.5 cm layer were higher than that of the 7.5-15 cm with different fertilization treatments, the reason may be that the incorporation of compost into the surface soil through tillage (Chen and Chen, 2017). On the other hand, higher SOC contents was observed in soil at 0–7.5 cm depth was probably due to promotes the cluster bean plant roots and soil microbial activities, which the aggregates cohesion and hydrophobicity, and soil aggregate stability were enhanced (Wallis and Horne, 1992), and thus increasing the SOC

The present results indicated that compared with and without IPNS, reduced SOC stability. The decomposed manure contained large amounts of labile organic C, which could be not only readily decomposed, but may promote microbial activity and thus increase the mineralization of inherent SOC (Van Groenigen et al., 2014). Compared with the without IPNS significantly affect organic C stability at two different depths in the cluster bean soil. On the one hand, increases in N availability may promote the decomposition of crop residues and inherent SOC (Brown et al., 2014), as evidenced by the significant and positive correlation between cumulative C release per gram of soil C with the content of soil total N. On the other hand, N addition is likely to reduce microbial biomass and thus C mineralization, particularly in the high-weathered and acid soil (Geisseler and Scow, 2014). In addition, changes in enzyme activities and microbial community composition on SOC decomposition under different fertilizer treatments addition needed further investigation (Cusack et al., 2011). Soil is a potential C sink, and its capacity to store and sequester organic C is determined by a dynamical equilibrium between C inputs from primary biomass production and organic material application and C outputs by mineralization (Kögel-Knabner et al., 2008). The higher C mineralization of the fertilized treatments represents higher losses of organic C and higher rates of organic matter turnover. In the present study, the SOC stocks cumulative of two depths nutrient management thorough with and without IPNS was 29.58 Mg ha⁻¹ in target yield 20 q ha⁻¹ with IPNS, 20.47 Mg ha⁻¹ target yield 20 q ha⁻¹ without IPNS treatments at 0-7.5 cm soil depth. This would have resulted in significantly higher C storage and sequestration in the with IPNS nutrient management system than those in the without IPNS nutrient management. The results indicated that without IPNS and with IPNS can maintain the SOC level, and if organic manure is applied, the SOC level can be significantly improved. A larger input over output of organic matter is the reason for the increase of SOC content in the without IPNS treatments. This implied that a high amount of organic material input through compost application is required for increasing the soil organic C pools. Therefore, higher SOC stocks in the cluster bean fields were attributed to both higher organic matter inputs and lower C decomposition rates (Kalbitz et al., 2013; Kögel-Knabner et al., 2008). In agreement with previous studies, organic manure and chemical fertilizer application could significantly enhance SOC stocks due to large additional C inputs in the cluster bean fields (Maillard and Angers, 2014; Sun et al., 2013; Zhang et al., 2012).

3.4 Different forms of Carbon Stocks

Data presented in table 4 and 5 reflects that different carbon stock during experimental year as influenced by the integrated plant nutrient system. During experimental year, the very labile carbon stock ranged from 0.553 to 1.018 (M g ha⁻¹), labile carbon stock 0.187 to 0.317 (M g ha⁻¹), less labile carbon stock 0.848 to 3.100 (M g ha⁻¹), recalcitrant carbon stock 1.421 to 1.388 (M g ha⁻¹), permanganate oxidizable carbon stock 0.292 to 0.297 (M g ha⁻¹), active pool stock 0.740 to 1.335 (M g ha⁻¹) and passive pool stock 2.269 to 4.488 (M g ha⁻¹) at both soil depths (0-7.5 cm and 7.5-15 cm) under T₂ *i.e.*, target yield 15 q ha⁻¹ to T₅ *i.e.*, target yield 20 q ha⁻¹ with IPNS. On the other hand, treatment T₅ *i.e.*, target yield 20 q ha⁻¹ with IPNS not only registered highest different carbon stock at 0-7.5 cm and 7.5-15 cm (Very labile carbon stock 0.748 and 1.018 (M g ha⁻¹), labile carbon stock 0.466 and 0.317 (M g ha⁻¹), less labile carbon stock 1.003 and 3.100 (M g ha⁻¹), recalcitrant carbon stock 1.885 and 1.388 (M g ha⁻¹), permanganate oxidizable carbon stock 0.328 and 0.297 (M g ha⁻¹), active pool stock 1.214 and 1.335 (M g ha⁻¹) and passive pool stock 2.889 and 4.488 (M g ha⁻¹ at 0-7.5 cm and 7.5-15 cm soil depth, respectively) but also significantly superior to all the rest treatments. The lowest yield was recorded under T₂ *i.e.*, target yield 15 q ha⁻¹. Order of different treatments in influencing the different carbon stock was T₅ > T₃ > T₄ > T₁ > T₂.

4. Conclusion

Application of IPNS and without IPNS significantly influenced total C and its different pools, carbon management index, carbon stock, active and passive pools of carbon of soil. Result concluded that soil test crop response recommendation under integrated plant nutrient system dose for target 20 q ha⁻¹ beneficial for the improvement in above mentioned parameters.

5. References

- Adhikari, K., Owens, P. R., Libohova, Z., Miller, D. M., Wills, S. A., Nemecek, J. Assessing soil organic carbon stock of Wisconsin, USA and its fate under future land use and climate change. *Science of the Total Environment*.2019: 667, 833-845.
- Ahirwal, J., Nath, A., Brahma, B., Deb, S., Sahoo, U.K., Nath, A.J. Patterns and driving factors of biomass carbon and soil organic carbon stock in the Indian Himalayan region. *Science of the Total Environment*.2021:770, 145292.

- Arshad, M.A., Schnitzer, M., Angers, D.A., Ripmeester, J.A. Effects of till vs no-till on the quality of soil organic matter. *Soil Biology and Biochemistry*.1990: 22(5), 595-599.
- Belay-Tedla, A., Zhou, X., Su, B., Wan, S., Luo, Y. Labile, recalcitrant, and microbial carbon and nitrogen pools of a tallgrass prairie soil in the US Great Plains subjected to experimental warming and clipping. *Soil Biology and Biochemistry*.2009: 41(1), 110-116.
- Benbi, D.K. Carbon sequestration for soil health enhancement and mitigating climate change. *Research Journal*.2015:49, 263.
- Bhattacharyya, R., Pandey, S.C., Bisht, J.K., Bhatt, J.C., Gupta, H.S., Tuti, M.D., Mahanta, D., Mina, B.L., Singh, R.D., Chandra, S., Srivastva, A.K. Tillage and irrigation effects on soil aggregation and carbon pools in the Indian sub-Himalayas. *Agronomy Journal*. 2013:105,101-112
- Benbi, D.K., Kiranvir, B.R.A.R., Sharma, S. Sensitivity of labile soil organic carbon pools to long-term fertilizer, straw and manure management in rice-wheat system. *Pedosphere*.2015:25(4), 534-545.
- Benbi, D.K., Sharma, S., Toor, A.S., Brar, K., Sodhi, G.P.S., Garg, A.K. Differences in soil organic carbon pools and biological activity between organic and conventionally managed rice-wheat fields. *Organic agriculture*.2018:8, 1-14.
- Benbi, D.K., Thind, H.S., Sharma, S., Brar, K., Toor, A.S. Bagasse ash application stimulates agricultural soil C sequestration without inhibiting soil enzyme activity. *Communications in Soil Science and Plant Analysis*.2017:48(15), 1822-1833.
- Benbi, D.K., Senapati, N. Soil aggregation and carbon and nitrogen stabilization in relation to residue and manure application in rice-wheat systems in northwest India. *Nutrient Cycling in Agroecosystems*.2010:87, 233-247.
- Bharali, A., Baruah, K.K., Bhattacharyya, P., Gorh, D. Integrated nutrient management in wheat grown in a northeast India soil: Impacts on soil organic carbon fractions in relation to grain yield. *Soil and Tillage Research*.2017:168, 81-91.

- Bhattacharyya, R., Tuti, M.D., Bisht, J.K., Bhatt, J.C., Gupta, H.S. Conservation tillage and fertilization impact on soil aggregation and carbon pools in the Indian Himalayas under an irrigated rice-wheat rotation. *Soil Science*. 2012: 177(3), 218-228.
- Blair, G.J., Lefroy, R.D., Lisle, L. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. *Australian Journal of Agricultural Research*. 1995:46(7), 1459-1466.
- Blair, N., Faulkner, R.D., Till, A.R., Poulton, P.R. Long-term management impacts on soil C, N and physical fertility. Part I: Broad balk experiment. *Soil Tillage and Research*, 2006: 91:30–38.
- Brar, B.S., Singh, K., Dheri, G.S. Carbon sequestration and soil carbon pools in a rice–wheat cropping system: effect of long-term use of inorganic fertilizers and organic manure. *Soil and Tillage Research*. 2013: 128, 30-36.
- Brown, K.H., Bach, E.M., Drijber, R.A., Hofmockel, K.S., Jeske, E.S., Sawyer, J.E., Castellano, M.J. A long- term nitrogen fertilizer gradient has little effect on soil organic matter in a high- intensity maize production system. *Global change biology*. 2014: 20(4), 1339-1350.
- Chan, K.Y., Bowman, A., Oates, A. Oxidizable organic carbon fractions and soil quality changes in an oxycpaleustalf under different pasture leys. *Soil science*. 2001:166(1), 61-67.
- Chatterjee, S., Bandyopadhyay, K.K., Pradhan, S., Singh, R., Datta, S.P. Effects of irrigation, crop residue mulch and nitrogen management in maize (*Zea mays* L.) on soil carbon pools in a sandy loam soil of Indo-gangetic plain region. 2018: *Catena* 165, 207-216.
- Chaudhary, S., Dheri, G.S., Brar, B.S. Long-term effects of NPK fertilizers and organic manures on carbon stabilization and management index under rice-wheat cropping system. *Soil and Tillage Research*. 2017:166, 59-66.
- Chen, Z., Ti, J.S., Chen, F. Soil aggregates response to tillage and residue management in a double paddy rice soil of the Southern China. *Nutrient Cycling in Agroecosystems*. 2017:109, 103-114.

- Chen, Z., Wang, H., Liu, X., Zhao, X., Lu, D., Zhou, J., Li, C. Changes in soil microbial community and organic carbon fractions under short-term straw return in a rice–wheat cropping system. *Soil and Tillage Research*.2017: 165, 121-127.
- Cusack, D.F., Silver, W.L., Torn, M.S., Burton, S.D., Firestone, M.K. Changes in microbial community characteristics and soil organic matter with nitrogen additions in two tropical forests. *Ecology*.2011: 92(3), 621-632.
- Das, D., Dwivedi, B. S., Singh, V.K., Datta, S.P., Meena, M.C., Chakraborty, D., Bandyopadhyay, K.K., Kumar, R., Mishra, R.P. Long-term effects of fertilisers and organic sources on soil organic carbon fractions under a rice–wheat system in the Indo-Gangetic Plains of north-west India. *Soil Research*.2016:55(3), 296-308.
- Das, T.K., Saharawat, Y.S., Bhattacharyya, R., Sudhishri, S., Bandyopadhyay, K.K., Sharma, A.R., Jat, M.L. Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize-wheat cropping system in the North-western Indo-Gangetic Plains. *Field Crops Research*.2018: 215, 222-231.
- Datta, A., Mandal, B., Badole, S., Majumder, S.P., Padhan, D., Basak, N., Barman, A., Kundu, R., Narkhede, W.N. Interrelationship of biomass yield, carbon input, aggregation, carbon pools and its sequestration in Vertisols under long-term sorghum-wheat cropping system in semi-arid tropics. *Soil and Tillage Research*.2018:184, 164-175.
- Gami, S.K., Lauren, J.G., Duxbury, J.M. Soil organic carbon and nitrogen stocks in Nepal long-term soil fertility experiments. *Soil and Tillage Research*.2009:106(1), 95-103.
- Geisseler, D., Scow, K.M. Long-term effects of mineral fertilizers on soil microorganisms–A review. *Soil Biology and Biochemistry*.2014:75, 54-63.
- Ghosh, A., Bhattacharyya, R., Meena, M.C., Dwivedi, B.S., Singh, G., Agnihotri, R., Sharma, C. Long-term fertilization effects on soil organic carbon sequestration in an Inceptisol. *Soil and Tillage Research*.2018:177, 134-144.

- Ghosh, M., Ashiq, W., Bhogilal Vasava, H., Gamage, D.N.V., Patra, P.K., Biswas, A. Short-term carbon sequestration and changes of soil organic carbon pools in rice under integrated nutrient management in India. *Agriculture*.2021:11(4), 348.
- Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N., Mandal, B. Organic amendments influence soil quality and carbon sequestration in the Indo-Gangetic plains of India. *Agriculture, Ecosystems & environment*.2012:156, 134-141.
- Gong, W., Yan, X.Y., Wang, J.Y., Hu, T.X., Gong, Y.B. Long-term manuring and fertilization effects on soil organic carbon pools under a wheat–maize cropping system in North China Plain. *Plant and Soil*.2009:314, 67-76.
- Hossain, M.B., Rahman, M.M., Biswas, J.C., Miah, M.M.U., Akhter, S., Maniruzzaman, M., Kalra, N. Carbon mineralization and carbon dioxide emission from organic matter added soil under different temperature regimes. *International Journal of Recycling of Organic Waste in Agriculture*.2017: 6, 311-319.
- Jat, H.S., Datta, A., Choudhary, M., Sharma, P.C., Yadav, A.K., Choudhary, V., Gathala, M.K., Jat, M.L., McDonald, A. Climate Smart Agriculture practices improve soil organic carbon pools, biological properties and crop productivity in cereal-based systems of North-West India. *Catena*.2019: 181, 104059.
- Jiang, X., Cao, L., Zhang, R. Changes of labile and recalcitrant carbon pools under nitrogen addition in a city lawn soil. *Journal of soils and sediments*.2014: 14, 515-524.
- Juhi, Singh, Y.K., Singh, B., Das, A., Kohli, A., Kumar, R., Padbhushan, R. Crop yields and soil organic matter pools in zero-till direct-seeded rice-based cropping systems as influenced by fertigation levels in the Indo-Gangetic plains in India. *Carbon Management*.2022: 13(1), 78-89.
- Kalambukattu, J.G., Singh, R., Patra, A.K., Arunkumar, K. Soil carbon pools and carbon management index under different land use systems in the Central Himalayan region. *Acta Agriculturae Scandinavica, Section B–Soil & Plant Science*.2013: 63(3), 200-205.

- Kalbitz, K., Kaiser, K., Fiedler, S., Kolbl, A., Amelung, W., Brauer, T., Cao, Z., Don, A., Grootes, P., Jahn, R., Schwark, L. The carbon count of 2000 years of rice cultivation. *Global Change Biology*.2013:19(4), 1107-1113.
- Kharia, S., Thind, H., Sharma, S., Sidhu, H., Jat, M., Singh, Y. Tillage and rice straw management affect soil enzyme activities and chemical properties after three years of conservation agriculture based rice-wheat system in north-western India. *International Journal of Plant & Soil Science*. 2017:15(6), 1-13.
- Kögel- Knabner, I., Ekschmitt, K., Flessa, H., Guggenberger, G., Matzner, E., Marschner, B., von Lützow, M. An integrative approach of organic matter stabilization in temperate soils: Linking chemistry, physics, and biology. *Journal of Plant Nutrition and Soil Science*.2008: 171(1), 5-13.
- Lal, R. Sequestration of atmospheric CO₂ in global carbon pools. *Energy & Environmental Science*.2008: 1(1), 86-100.
- Lopez- Capel, E., Krull, E.S., Bol, R., Manning, D.A. Influence of recent vegetation on labile and recalcitrant carbon soil pools in central Queensland, Australia: evidence from thermal analysis- quadrupole mass spectrometry- isotope ratio mass spectrometry. *Rapid Communications in Mass Spectrometry: An International Journal Devoted to the Rapid Dissemination of Up- to- the- Minute Research in Mass Spectrometry*.2008: 22(11), 1751-1758.
- Lorenz, K., Lal, L. Subsoil organic carbon pool. *Encyclopaedia of Soil Science*, third edition published Taylor and Francis.2016.
- Maia, S.M.F., Xavier, F.A.S., Oliveira, T.S., Mendonça, E.S., Araújo Filho, J.A.,. Organic carbon pools in a Luvisol under agroforestry and conventional farming systems in the semi-arid region of Ceará, Brazil. *Agroforestry Systems*.2007: 71, 127-138.
- Maillard, E., Angers, D.A. Animal manure application and soil organic carbon stocks: A meta- analysis. *Global Change Biology*.2014: 20(2), 666-679.

- Majumder, B., Mandal, B., Bandyopadhyay, P.K., Chaudhury, J. Soil organic carbon pools and productivity relationships for a 34 year old rice–wheat–jute agroecosystem under different fertilizer treatments. *Plant and soil*.2007: 297, 53-67.
- Mandal, A., Toor, A.S., Dhaliwal, S.S. Assessment of sequestered organic carbon and its pools under different agricultural land-uses in the semi-arid soils of south-western Punjab, India. *Journal of Soil Science and Plant Nutrition*.2020: 20, 259-273.
- McLauchlan, K.K., Hobbie, S.E., Post, W.M. Conversion from agriculture to grassland builds soil organic matter on decadal timescales. *Ecological Applications*.2006: 16(1), 143-153.
- Moharana, P.C., Sharma, B.M., Biswas, D.R., Dwivedi, B.S., Singh, R.V. Long-term effect of nutrient management on soil fertility and soil organic carbon pools under a 6-year-old pearl millet–wheat cropping system in an Inceptisol of subtropical India. *Field Crops Research*.2012: 136, 32-41.
- Naik, S. K., Maurya, S., Bhatt, B.P. Soil organic carbon stocks and fractions in different orchards of eastern plateau and hill region of India. *Agroforestry Systems*.2016: 91, 541-552.
- Nath, A.J., Brahma, B., Sileshi, G.W., Das, A.K. Impact of land use changes on the storage of soil organic carbon in active and recalcitrant pools in a humid tropical region of India. *Science of the total Environment*.2018:624, 908-917.
- Parihar, C.M., Jat, S.L., Singh, A.K., Datta, A., Parihar, M.D., Varghese, E, Bandyopadhyay, K.K., Nayak, H.S., Kuri, B.R., Jat, M. L. Changes in carbon pools and biological activities of a sandy loam soil under medium- term conservation agriculture and diversified cropping systems. *European Journal of Soil Science*.2018: 69(5), 902-912.
- Parihar, C.M., Parihar, M.D., Sapkota, T.B., Nanwal, R.K., Singh, A.K., Jat, S.L., Nayak, H.S., Mahala, D.M., Singh, L.K., Kakraliya, S.K., Jat, M.L. Long-term impact of conservation agriculture and diversified maize rotations on carbon pools and stocks, mineral nitrogen fractions and nitrous oxide fluxes in Inceptisol of India. *Science of the Total Environment*.2018:640, 1382-1392.

- Paul, E.A., Paustian, K.H., Elliott, E.T., Cole, C.V. Soil Organic Matter in Temperate Agroecosystems Long Term Experiments in North America. CRC Press.1996.
- Paul, O.O., Sekhon, B.S., Sharma, S. Spatial variability and simulation of soil organic carbon under different land use systems: geostatistical approach. *Agroforestry Systems*.2019:93, 1389-1398.
- Ramesh, T., Manjiah, K. M., Mohopatra, K. P., Rajasekar, K., Ngachan, S. V. Assessment of soil organic carbon stocks and fractions under different agroforestry systems in subtropical hill agroecosystems of north-east India. *Agroforestry Systems*.2015: 89, 677-690.
- Rovira, P., Vallejo, V.R. Labile and recalcitrant pools of carbon and nitrogen in organic matter decomposing at different depths in soil: an acid hydrolysis approach. *Geoderma*. 2002: 107(1-2), 109-141.
- Saha, M., Das, M., Sarkar, A. Distinct nature of soil organic carbon pools and indices under nineteen years of rice based crop diversification switched over from uncultivated land in eastern plateau region of India. *Soil and Tillage Research*.2021: 207, 104856.
- Sahoo, U.K., Singh, S.L., Gogoi, A., Kenye, A., Sahoo, S.S. Active and passive soil organic carbon pools as affected by different land use types in Mizoram, Northeast India. *PloS One*. 2019: 14(7), e0219969.
- Sherrod, L.A., Peterson, G.A., Westfall, D.G., Ahuja, L.R. Soil organic carbon pools after 12 years in no- till dryland agroecosystems. *Soil Science Society of America Journal*.2005: 69(5), 1600-1608.
- Singh, P., Benbi, D.K. Nutrient management effects on organic carbon pools in a sandy loam soil under rice-wheat cropping. *Archives of Agronomy and Soil Science*.2018: 64(13), 1879-1891.
- Snyder, J.D., Trofymow, J.A. A rapid accurate wet oxidation diffusion procedure for determining organic and inorganic carbon in plant and soil samples. *Communications in Soil Science and Plant Analysis*.1984: 15(5), 587-597.

- Sun, Y., Huang, S., Yu, X., Zhang, W. Stability and saturation of soil organic carbon in rice fields: evidence from a long-term fertilization experiment in subtropical China. *Journal of Soils and Sediments*.2013: 13, 1327-1334.
- Tian, K., Zhao, Y., Xu, X., Hai, N., Huang, B., Deng, W. Effects of long-term fertilization and residue management on soil organic carbon changes in paddy soils of China: A meta-analysis. *Agriculture, Ecosystems & Environment*.2015: 204, 40-50.
- Tirol-Padre, A., Ladha, J.K. Assessing the reliability of permanganate- oxidizable carbon as an index of soil labile carbon. *Soil Science Society of America Journal*.2004: 68(3), 969-978.
- Van Groenigen, K.J., Qi, X., Osenberg, C.W., Luo, Y., Hungate, B.A. Faster decomposition under increased atmospheric CO₂ limits soil carbon storage. *Science*.2014:344(6183), 508-509.
- Walkley, A., Black, I.A. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. *Soil science*.1934: 37(1), 29-38.
- Wallis, M.G., Horne, D.J., Palmer, A.S. Water repellency in a New Zealand development sequence of yellow brown sands. *Soil Research*.1993: 31(5), 641-654.
- Wang, Q., Wang, Y., Wang, Q., Liu, J. Impacts of 9 years of a new conservational agricultural management on soil organic carbon fractions. *Soil and Tillage Research*.2014: 143,1-6.
- Yagi, R., Ferreira, M.E., Cruz, M.C.P.D., Barbosa, J.C., Araújo, L.A.N.D. Soil organic matter as a function of nitrogen fertilization in crop successions. *Scientia Agricola*.2005: 62, 374-380.
- Yan, Y., He, H., Zhang, X., Chen, Y., Xie, H., Bai, Z., Zhu, P., Ren, J., Wang, L. Long-term fertilization effects on carbon and nitrogen in particle-size fractions of a Chinese Mollisol. *Canadian Journal of Soil Science*.2012: 92(3), 509-519.

Zhang, W., Xu, M., Wang, X., Huang, Q., Nie, J., Li, Z., Li, S., Hwang, S.W., Lee, K.B. Effects of organic amendments on soil carbon sequestration in paddy fields of subtropical China. *Journal of soils and sediments*.2012: 12, 457-470.

UNDER PEER REVIEW

Table 2. Effect of STCR approach on soil carbon fractions of different soil depth

Treatments	0-7.5 cm soil depth						7.5-15 cm soil depth					
	C _{VLC}	C _{LC}	C _{LLC}	C _{RC}	C _{TOC}	C _{POC}	C _{VLC}	C _{LC}	C _{LLC}	C _{RC}	C _{TOC}	C _{POC}
T ₁ -General recommended dose	0.534	0.179	0.771	1.58	3.07	0.258	0.311	0.111	0.543	1.12	2.08	0.121
T ₂ -Target yield 15 q ha ⁻¹	0.470	0.159	0.720	1.21	2.55	0.247	0.289	0.121	0.499	1.01	1.92	0.112
T ₃ -Target yield 15 q ha ⁻¹ with IPNS	0.652	0.359	0.850	1.59	3.45	0.282	0.423	0.132	0.588	1.23	2.37	0.127
T ₄ -Target yield 20 q ha ⁻¹	0.531	0.170	0.723	1.39	2.81	0.251	0.307	0.119	0.467	1.08	1.97	0.119
T ₅ -Target yield 20 q ha ⁻¹ with IPNS	0.673	0.418	0.901	1.70	3.69	0.295	0.441	0.137	0.601	1.34	2.52	0.129
SEm _±	0.042	0.009	0.019	0.087	0.123	0.011	0.033	0.005	0.022	0.06	0.089	0.004
Cd (P = 0.05)	0.129	0.027	0.059	0.27	0.38	0.033	0.102	0.016	0.067	0.18	0.27	0.012

*C_{VLC}- very labile carbon, C_{LC}-labile carbon, C_{LLC}-less labile carbon, C_{RC}-recalcitrant carbon, C_{TOC}- total organic carbon, C_{POC}-permanganate oxidizable carbon

Table 3. Effect of with IPNS and without IPNS approach on Carbon stock (M g ha⁻¹), Carbon management index (%), active pool (g C kg⁻¹ soil) and passive pool (g C kg⁻¹ soil) at 0-7.5 and 7.5-15 cm soil depth

Treatments	0-7.5 cm soil depth				7.5-15 cm soil depth			
	CS	CMI	AP	PP	CS	CMI	AP	PP
T ₁ -General recommended dose	21.38	100.0	0.713	2.35	17.24	100.00	0.421	1.663
T ₂ -Target yield 15 q ha ⁻¹	19.59	97.62	0.628	1.93	16.08	92.77	0.409	1.512
T ₃ -Target yield 15 q ha ⁻¹ with IPNS	28.73	125.7	1.011	2.44	18.38	104.29	0.554	1.818
T ₄ -Target yield 20 q ha ⁻¹	20.47	95.61	0.701	2.11	15.20	99.02	0.425	1.548
T ₅ -Target yield 20 q ha ⁻¹ with IPNS	29.58	129.2	1.091	2.60	23.68	105.75	0.578	1.943
SEm _±	0.91	9.535	0.048	0.09	1.20	3.61	0.034	0.081
Cd (P = 0.05)	2.81	29.38	0.148	0.27	3.70	NS	0.105	0.249

*CS-carbon stock, CMI-carbon management index, AP- active pool and passive pool

Table 4. Effect of with IPNS and without IPNS approach on different Carbon stock (M g ha⁻¹) at 0-7.5 cm soil depth

Treatments	VLC Stock	LC Stock	LLC Stock	RC Stock	POC Stock	AP Stock	PP Stock
T ₁ -General recommended dose	0.603	0.203	0.874	1.793	0.293	0.806	2.269
T ₂ -Target yield 15 q ha ⁻¹	0.553	0.187	0.848	1.421	0.292	0.740	2.667
T ₃ -Target yield 15 q ha ⁻¹ with IPNS	0.739	0.407	0.963	1.799	0.319	1.146	2.762
T ₄ -Target yield 20 q ha ⁻¹	0.622	0.200	0.848	1.628	0.295	0.821	2.476
T ₅ -Target yield 20 q ha ⁻¹ with IPNS	0.748	0.466	1.003	1.885	0.328	1.214	2.889
SEm±	0.047	0.012	0.026	0.101	0.015	0.055	0.107
Cd (P = 0.05)	0.144	0.037	0.081	0.312	NS	0.170	0.330

* VLC- Very labile carbon stock, LC-labile carbon stock, LLC-less labile carbon stock, RC-Recalcitrant carbon stock, POC-Parmaganate oxidizable carbon stock, AP- Active pool stock and PP- Passive pool stock

Table 5. Effect of with IPNS and without IPNS approach on different Carbon stock (M g ha⁻¹) at 7.5-15 cm soil depth

Treatments	VLC Stock	LC Stock	LLC Stock	RC Stock	POC Stock	AP Stock	PP Stock
T ₁ -General recommended dose	0.755	0.268	2.718	1.319	0.294	1.023	4.036
T ₂ -Target yield 15 q ha ⁻¹	0.706	0.294	2.476	1.221	0.274	1.000	3.696
T ₃ -Target yield 15 q ha ⁻¹ with IPNS	0.983	0.306	2.865	1.370	0.294	1.288	4.235
T ₄ -Target yield 20 q ha ⁻¹	0.748	0.289	2.634	1.137	0.291	1.037	3.771
T ₅ -Target yield 20 q ha ⁻¹ with IPNS	1.018	0.317	3.100	1.388	0.297	1.335	4.488
SEm±	0.078	0.012	0.137	0.052	0.009	0.079	0.187
Cd (P = 0.05)	0.239	0.036	0.423	0.160	NS	0.245	0.576

* VLC- Very labile carbon stock, LC-labile carbon stock, LLC-less labile carbon stock, RC-Recalcitrant carbon stock, POC-Parmaganate oxidizable carbon stock, AP- Active pool stock and PP- Passive pool stock