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Long term conservation tillage and organic nutrient managements foster the biological properties and carbon sequestering capability in rice-wheat rotations of NWIGP: A review

Himanshu Tiwari, RK Naresh, Dhiru Kumar Tiwari, Manisha, Yogesh Kumar, Ankit Tiwari, Shubhendu Singh and Ravindra Sachan

Abstract
Poor soil fertility and soil degradation induced by persistent conventional farming with repeated tillage and removal or in situ burning of crop residue are major limitations to food security and environmental sustainability. However, degraded agricultural lands with depleted soil organic carbon (SOC) stocks are capable of soil carbon restoration through improved management practices like aggregation, humification and deep placement of C that can increase SOC sequestration. The fate of SOC in cropland soils plays a significant role in both sustainable agricultural production and climate change mitigation. Tillage systems can influence C sequestration by changing aggregate formation and C distribution within the aggregate. Average SOC concentration of the control treatment was 0.54%, which increased to 0.65% in the RDF treatment and 0.82% in the RDF+FYM treatment and increased enzyme activities, which potentially influence soil nutrients dynamics under field condition. Compared to F_1 control treatment the RDF+FYM treatment sequestered 0.28 Mg C $ha^{-1}yr^{-1}$ whereas the NPK treatment sequestered 0.13 Mg C $ha^{-1}yr^{-1}$. As tillage intensity increased there was a redistribution of SOC in the profile, but it occurred only between ZT and PRB since under CT, SOC stock decreased even below the plow layer. Increased SOC stock in the surface 50 kg m^{-2} under ZT and PRB was compensated by greater SOC stocks in the 50-200 and 200-400 kg m^{-2} interval under residue retained, but SOC stocks under CT were consistently lower in the surface 400 kg m^{-2}. Soil carbon (C) pools and biological indicator plays an important role in maintaining soil quality. Vermicompost + NPK treatment recorded the highest oxidizable organic carbon (0.69%), dissolved organic carbon (0.007%) and microbial biomass carbon (0.01%), followed by FYM + NPK, GL + NPK and RS + NPK as compared to control. Rice straw + NPK sequestered the highest amount of carbon dioxide (CO_2) as the total organic carbon (91.10 t ha^{-1}) and passive pool of carbon (85.64 t ha^{-1}), whereas VC + NPK resulted in the highest amount of CO_2 (10.24 t ha^{-1}) being sequestered as the active pool of carbon, followed by FYM + NPK (8.33 t ha^{-1}) and GL + NPK (7.22 t ha^{-1}). The soil microbial biomass carbon significantly varied across the treatments from 129.4 to 412.1 µg g^{-1} which comprises 2.4 to 4.4% of the SOC. The highest bacterial count (8.95 log cfu g^{-1} soil) was recorded in RDF + *Azolla* treatment, whereas fungal count was the maximum (7.47 log cfu g^{-1} soil) in RDF + FYM treatment. All the enzymatic activities responded significantly to the INM practices, but the trend of response was different for different enzymes. The highest dehydrogenase (223.6 µg TTF g^{-1} soil 24 h^{-1}) and urease (4.1 µg NH_4-N g^{-1} soil 2 h^{-1}) activities were recorded in RDF + *Azolla*, while phosphomonoeaterase (337.4 µg *p*-nitrophenol g^{-1} soil h^{-1}) and fluorescein diacetate hydrolysis (10.0 µg fluorescein g^{-1} soil h^{-1}) activities were found to be the maximum in RDF + FYM. However, Total organic carbon input of soil was increased by 10.2 - 23.3 kg $Cha^{-1}yr^{-1}$, and increment rate in the appended manure treatments were much higher than those in the control and inorganic fertilizer treatments. Soil organic carbon retention in the topsoil (0 - 20 cm) decreased by 0.11 - 0.14 $tha^{-1}yr^{-1}$ in the control, N and NP treatments; nevertheless, soil organic carbon sequestration rates varied from 0.03 to 0.20 $tha^{-1}yr^{-1}$ in the NPK and appended organic manure treatments. Adding carbon materials to soil is thereby not directly sequestration, as interaction of appropriately designed materials with the soil Microbiome can result in both: metabolization and thereby non-sustainable use of the added carbon, or-more favourably-a biological amplification of human efforts and sequestration of extra CO_2 by microbial growth.

Keywords: Conservation tillage, carbon sequestration, enzymatic activity, microbial activity

Introduction
There is an increase in atmospheric C concentration by 31% which is 270 ± 30 Pg since industrial uprising due to the change in land use patterns. Depletion of SOM has contributed up to 78 ± 12 Pg in the atmosphere. Agricultural soils have lost two-thirds of the original SOC

with a cumulative loss of 30–40 Mg C ha^{-1}. Atmospheric C removal and storing it in the soils is one of the best options. From soils, agricultural soils are thought to be a major sink and can sequester more and more quantities of C if we adopt agro-forestry. It has received widespread credit due to its advantages of helping in agricultural sustainability CC mitigation (Lal, 2004) [32]. The CS potential of agro-forestry systems is estimated between 12 and 228 Mg ha^{-1}. So, based on the Earth's total suitable area for crop production, which is 585–1215 × 10^6 ha, a total of 1.1–2.2 Pg C can be sequestered in the agricultural soils in the next 50 years (Albrecht and Kandji, 2003) [2]. Overall, the agriculture sector has a great potential for CS in the soil as well as in crop plants. Changes in agricultural practice and managements can also result in enhanced CS in them. It is presumed that if we change the management practice, it will result in decreased crop yields but the net C flux can be greater under the new system. It will only happen when crop demand remains the same and additional lands are brought into production. Conversely, if increasing crop yields lead to land abandonment, the overall C savings from changes in management will be greater than when soil CS alone is considered (West and Marland, 2003) [59]. Application of organic amendments and N fertilizer incurs C emissions to the atmosphere, which must be deducted by increasing SOM. Application of manures is important for maintaining agricultural soil health (Baker *et al*., 2007) [7].

Intensive agriculture can guarantee food security worldwide, but at the cost of detrimental effects on soil health (Palm *et al*., 2014). Long-term application of nitrogenous fertilizers may cause several problems like lowering soil organic carbon (SOC), increasing soil acidification and poor physical properties (Celik *et al*., 2010) [12], as it has been observed in several long-term experiments (Nambiar, 1994) [38], while the integration of organic sources sustains the productivity (Baishya *et al*., 2015) [5]. Although organic and inorganic fertilizers are used primarily to increase nutrient availability to plants, they can affect the population, composition, and function of soil microorganisms (Marschner *et al*., 2003) [35].

Farmyard manure (FYM), crop stubbles, and *Azolla* represent important sources of organic matter in rice –wheat crops managed under integrated nutrient management (INM) systems (Baishya *et al*. 2015) [5] and are likely to maintain C level sustaining the soil health under long-term (Benbi and Senapati, 2010) [10]. For assessing the effects of agricultural practices on soil quality, the microbial community has been considered as an important indicator because a shifting in their community structures is coupled with changes in soil quality (Sun *et al*., 2015) [52]. Although the soil quality depends on several soil parameters, biological processes are the most sensitive and significant (Drobnik *et al*., 2018) [21]. The role of soil organisms is crucial, because they are responsible of organic matter decomposition, nutrient cycling, soil fertility and quality for which maintaining high levels of microbial diversity in soil is the key for sustainable agriculture (Bünemann *et al*., 2018) [11].

Soils' microbial diversity is considered important for ecosystems' functioning, both in relation to direct interactions with plants with respect to nutrient transformations and organic C cycling (Adak and Sachan, 2009) [1]. Notwithstanding the changes in SOC pool and nutrient transformations caused by soil micro-organisms, cropping systems are known to influence soil microbial biomass and its diversity which impacts enzyme activity in soil (Sharma *et al*., 2019) [59]. Soil enzymatic activities are referred as 'sensors' of soil degradation as they manifest the physico-chemical conditions of soil and are indicators of its microbial status (Baum *et al*., 2003) [8]. Soil microbial biomass is considered more reactive than the SOC to depict changes occurring in soil environment (Benbi *et al*., 2015) [9]. Indeed, the impacts of soil management induced changes are more readily discernible via soil microbial biomass and the enzymatic activity (Sharma *et al*., 2019; Benbi *et al*., 2015) [59, 9]. There exists a direct linkage between seasonal fluctuations in soil microbial biomass, which in turn influences soil organic matter turnover as well as nutrient cycling in soils. Soil enzymatic activity is highly sensitive to the change in soil environment, and is therefore, necessary to understand the mechanisms of SOC dynamics.

The functional potentialities of microorganisms are indicated by the soil microbial biomass and enzymatic activities in soil. Estimation of SMBC is considered as the most sensitive and important biological indicator for assessing both short as well as long-term changes in soil fertility and quality (Bakhshandeh *et al*., 2019) [6], although it comprises only 1–5% of the total organic carbon (Malik *et al*., 2018) [34]. Soil enzymes are important for their intimate relationship to soil microbial activities (Ramirez *et al*., 2012) [43], which directly affect soil stability and fertility, and are strongly involved in the dynamics of soil nutrient transformations and soil quality (Dick, 1994) [19].

Conservation tillage operations have often been reported to enhance soil organic carbon sequestration whereas simultaneously mitigate the carbon (C) emissions associated with agricultural inputs such as fertilizers and on-farm fuels (West and Marland, 2002) [58]. However, there is considerably uncertainty in the estimation of the carbon sink/source of an agricultural system. For example, Snyder *et al*. (2009) [53] has showed that the agricultural fields not only are a carbon sinks but also a carbon source because of the application of tillage and fertilizer treatments. Tillage and fertilizer methods always support food, energy, and air for the development of soil organisms, thus increasing the decomposition rate of residues and soil respiration and ultimately resulting in that the stable soil organic carbon is awkward (Wang *et al*., 2009) [56]. However, Zhao *et al*. (2010) [635] also found that the carbon uptake of a farmland in China's coastal areas is significantly higher than that of C emissions. Chen *et al*. (2015) showed that rotary tillage with straw incorporation and no tillage with straw mulching display a C sink, while moldboard plow tillage with or without straw shows a carbon source in paddy soil

Carbon loss from soil does not only hold important ramifications for global climate change but also has massive effects on global food security (Lal, 2004) [32]. It was claimed that the world will face a severe food crisis unless food production is increased by 60~110% from 2005 to 2050 (Tilman *et al*., 2011) [55], while at the same time, arable soil fertility is constantly decreasing due to over-farmed land substantially losing soil organic matter (SOM) and the essential nutrients that adhere to SOM. Previous investigations have revealed that SOM depletes for various reasons, e.g., soil erosion due to large scale reclamation (Lal, 2004) [32], improper plowing, and excessive use of fertilizers (Oost *et al*., 2007) [41] even a warming climate. Consequently, new techniques that enable to enrich soil carbon have to become first priority in worldwide science to ease the food, and climate crisis that will occur in the future has already started. Holistic production-management systems that promote and enhance agro-ecosystem health are necessary, in order to protect our soils while maintaining high productive capacities contributing to ecological, economic and social sustainability. We hypothesize that the rice–wheat cropping system play a crucial role in regulating soil biology and biochemical changes due to change in soil microbial biomass and enzymatic activities which are function of soil C pools that alters differentially under different organic nutrient management. The objectives of the present review study were (i) to decipher the respective soil C pools, enzymatic activity and their relationship with chemical and microbial properties of soils under rice–wheat cropping systems, and (ii) to use them as a potential soil health indicator as a quick tool to frame a strategy to enhance C storage for mitigating the accelerated environmental degradation due to rice–wheat cropping in the NWIGP.

Longer-term SOC storage

Soil organic matter is the complex organic substances consisting of organic residues, humic substances, microbial bodies that undergo decomposition at various stages. It influences plant growth and yield by improving soil structure and acts as a reservoir of plant nutrients containing 2.5 Eg carbon (1Eg = 10^{18} g). The formation of the clay-humus complex increases the buffering capacity of the soil and forms stable complexes with some metals to make them available for plant uptake. Soil carbon is mainly present as organic matter or humus and varies from 1% (coarse-textured soil) to 3.5% (grassland). But Indian soils are deficient in SOC due to prevalence of the tropical, sub-tropical, arid and semi-arid climatic condition, persistent tillage practice, non-judicious use of agrochemicals, removal of crop residue from land etc.

Mineral-associated SOC storage depends on availability of appropriate sink minerals. Saturation takes place when the store of suitable minerals has been utilized, and leads to particularly low CSEs in some soils (Chenu *et al*., 2019; Lal, 2018) [13, 33]. Basalt weathering supplies abundant Ca, Mg, Al and Fe to the soil surface layer providing mineral surfaces for the formation of mineral associated SOC, and improving soil aggregation (Kallenbach *et al*., 2016) [30] [Fig. 1b]. Biochar application does not increase the mineral surface sink, but it can increase the conversion efficiency of rhizodeposits into mineral-associated SOC decrease SOC degradation and foster the formation of micro-aggregates that promote further SOC stabilization (Fig. 1b).

Tang *et al*. (2022) [54] also found that carbon monoxide (CO), a minor, but relevant C-related gas emitting from soil is delivered by the abiotic degradation of carbohydrates and lignin from plant litter. The incomplete chemical oxidation of organic C in soil at low oxygen partial pressures is an additional path of CO formation and release. Biotic reduction of CO_2 is another source of CO in soil, which is performed by anaerobic bacteria, e.g., sulfate-reducing bacteria or methanogenic bacteria (Fig1a). CO is also a well-known energy source for the growth of microbes. In carboxydotrophic bacteria operate by oxidizing CO with H_2O to CO_2 and $2H^+ + 2e^-$ and depend on CO dehydrogenase (CODH). Pseudomonas carboxydovorans (Conrad and Seiler, 1980) [17].

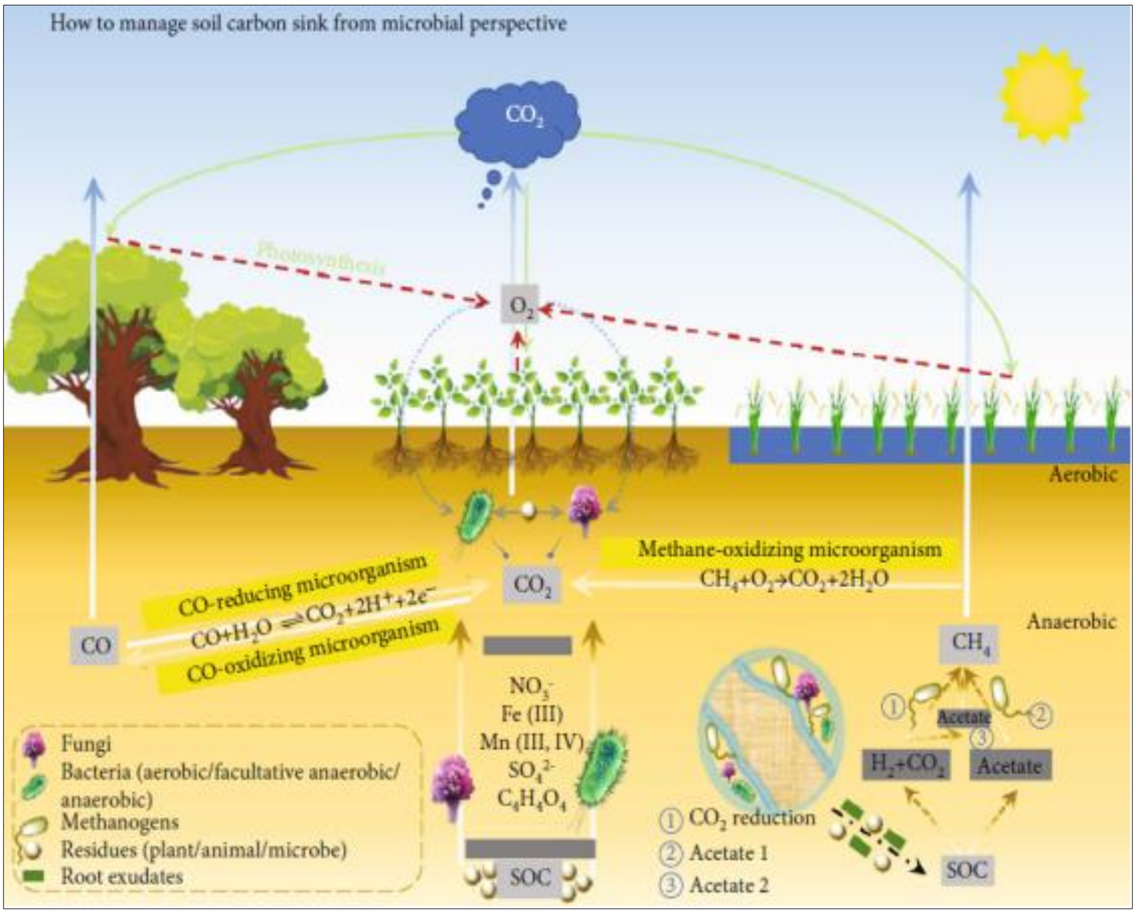

Fig 1a: Schematic diagram of microbial involvement in carbon emissions [Tang *et al*., 2022] [54]

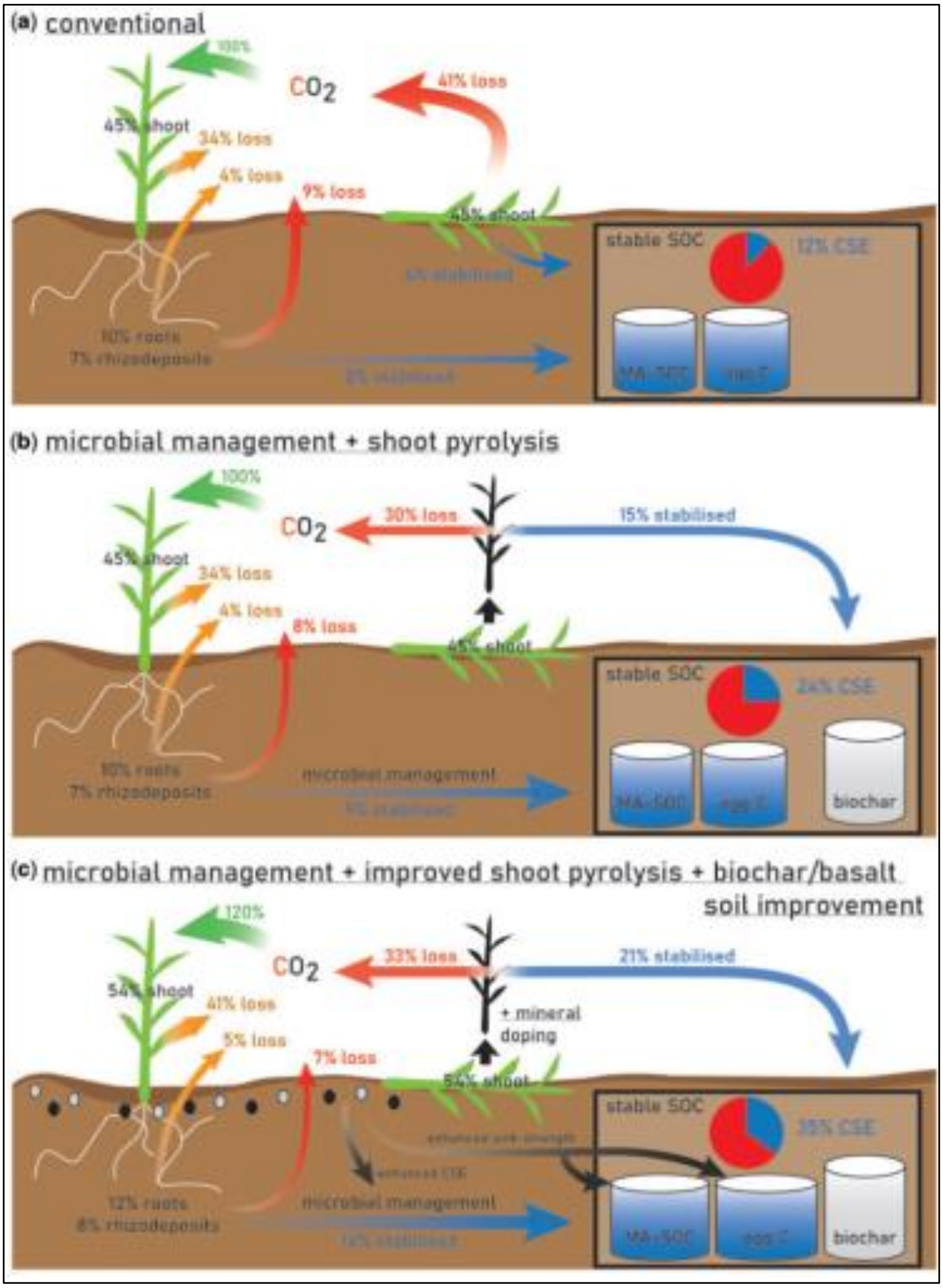

Fig 1b: Relative Carbon Sequestration Efficiency (CSE) of above- and belowground plant carbon into stable forms of soil carbon. (a) Conventional cropping systems, (b) system with plant shoot pyrolysis (+ biochar soil application) and management of microbial composition and (c) system with mineral doping of feedstock [Source: Buss *et al*., 2021]

Cheng *et al*. (2018) [16] revealed that crop biomass carbon was increased by 39.9 to 77.2% compared to unfertilized control due to thirty-three years fertilizer application in the rice-wheat cropping systems. The unfertilized control had the lowest biomass carbon, whereas crop biomass carbon was the highest in the hMNPK treatment. Annual crop biomass carbon was generally higher with manure combined with chemical fertilizer compared to chemical fertilizer or manure alone treatments. Averagely, annual crop biomass carbon was 5 t ha^{-1} in N treatment, approximate 6 tha^{-1} in NP, NPK, M treatments, and approximate 7 tha^{-1} in MN, MNP, MNPK, hMNPK treatments. However, averagely, the lowest total carbon input was 1.44 $tha^{-1}yr^{-1}$ in the control treatment, whereas the highest one was 5.80 t $ha^{-1}yr^{-1}$ in the hMNPK treatment. The average annual carbon inputs in the manure treatments (M, MN, MNP, MNPK, hMNPK) were 1.95 to 2.74 times of that in the NPK treatment (2.12 $tha^{-1}yr^{-1}$). Moreover, Soil organic carbon declined at a rate of 30.1, 21.9, and 14.1 mg kg^{-1} carbon in the control, N, and NP treatments every year, respectively. Applications of organic manures combined with inorganic fertilizers (MN, MNP, MNPK, hMNPK) significantly increased soil organic carbon contents compared to the corresponding application of inorganic fertilizers alone (N, NP, NPK). The balanced application of the NPK fertilizer increased soil organic C contents in comparison to the unbalanced application of inorganic fertilizers (N, NP).

Sharma *et al*. (2020) [58] reported that the recalcitrant C (Fract. 4) was significantly higher in uncultivated, compared with cultivated soils under rice–wheat and cotton–wheat system. The cultivated soils under rice–wheat had significantly higher (64.8%) recalcitrant C pool, compared with soils under cotton–- wheat cropping system. Relative preponderance of these four fractions of variable oxidizability in the uncultivated and cultivated soils follows an order: Fract. 1<Fract. 2<Fract. 3<Fract. 4. The Fract. 1 was the smallest fraction, comprising 12.4%–16.8% of TOC; and was significantly higher in the uncultivated, compared with cultivated soils (Fig. 2a). The stable C pool (Fract. 3+Fract. 4) comprised 68.8% of TOC in the uncultivated soils, compared with 68.5% in rice–- wheat, and 61.9% in cotton–wheat soils. However, microbial quotients contributed maximum to SQI of soils under cotton–wheat (0.297) followed by rice–wheat (0.293) and the minimum in the undisturbed soils (0.264). The relative order of contribution of the selected indicators towards SQI was 47.7% for BSR, 36.4% for microbial quotients, 15.9% for Fract. 2 (Fig. 2b). There occurs a rapid conversion of organic inputs and labile C to stable forms with longer persistence under favorable conditions of moisture, root biomass and minimum soil disturbance. Intense tillage disrupts soil structure to expose soil organic matter encapsulated in macro-aggregates. The conventional tillage accelerates oxidation of soil organic matter by soil microbes due to change in moisture and aeration status influencing soil microbes and microbial activity (Doran and Smith, 1987) [20]. It impacts TOC pool when the undisturbed lands are converted to arable agriculture under intense tillage (Saviozzi *et al*., 1994) [47].

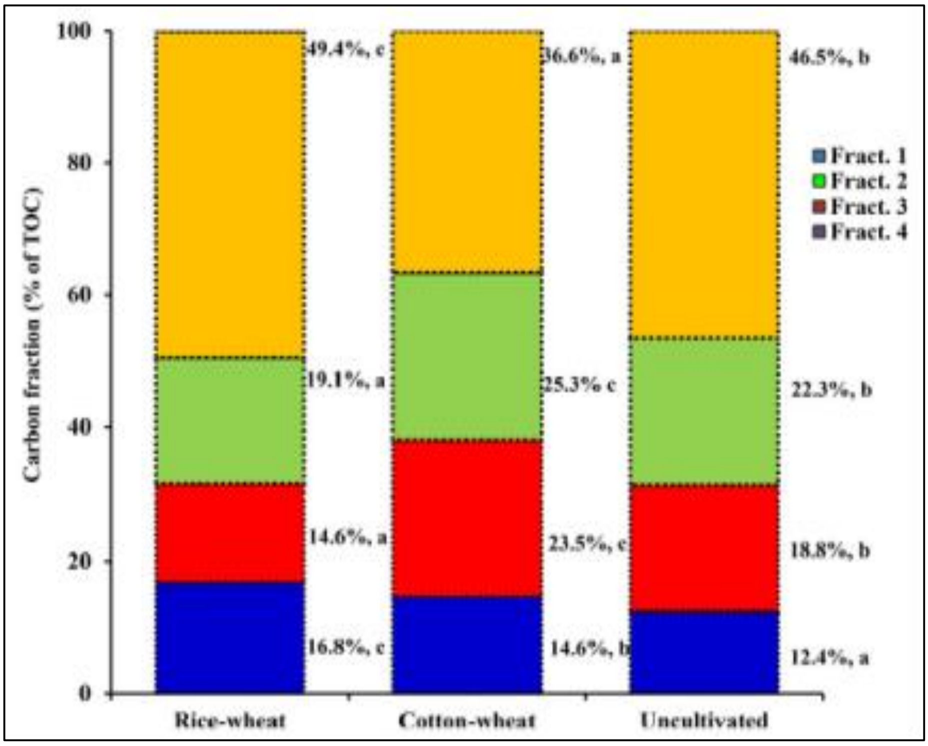

Fig 2a: Distribution of soil organic carbon fractions of varying oxidizability (as % of total organic carbon) surface (0–15 cm) layer of cultivated soils under rice–wheat cropping system and uncultivated soils [Source: Sharma *et al*., 2020] [58].

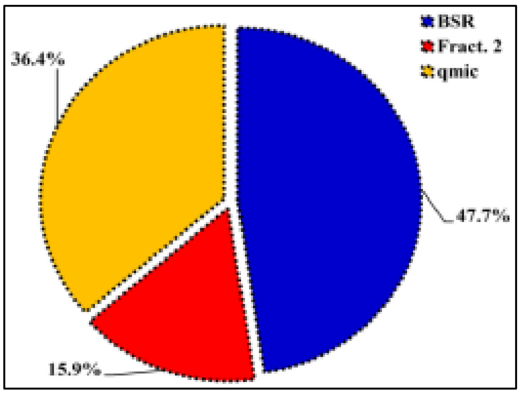

Fig 2b: Soil quality indicators towards soil quality index (SQI) of cultivated soils under rice–wheat cropping system and the uncultivated soils [*Source*: Sharma *et al*., 2020] [58].

Ghosh *et al*. (2021) [24] also found that NPK only and all organic manure + NPK treatments showed increases in other carbon fractions over control. Accordingly, the TOC content was highest (2.81%) in plots the received RS + NPK. The increase was 79% greater than the initial TOC of the soil. Although the other organic manures such as GL + NPK, FYM + NPK and VC + NPK showed significant increases in TOC content compared to the control, no significant differences were observed among them. Oxidizable organic carbon and DOC values significantly improved for all organic manure plots compared to control. Vermicompost + NPK plots had the highest OOC (0.69%) and DOC (0.007%) values compared to the control, whereas plots that received NPK only had the lowest OOC (0.51%) and DOC (0.004%) (Fig.3a). Further, OOC and DOC significantly increased in FYM + NPK, GL + NPK and RS + NPK plots compared to control. The MBC values in soil (0–15 cm depth) significantly increased with the application of organic manures. The highest increase in MBC was observed in VC + NPK plots, while chemical fertilizer plots had the lowest values compared to the control. In addition, increases of MBC followed the order of FYM + NPK (27.4%), GL + NPK (26.4%) and RS + NPK (20.3%). Further, MBC values increased by 9.1 and 13.5% in the control and NPK only plots, respectively, over the initial content (Fig.3a).

However, carbon sequestration in terms of both TOC (91.11 t ha^{-1}) and PPC (88.74 t ha^{-1}) was highest in RS + NPK plots as compared to that of control. Plots that received chemical fertilizer only sequestered 19.02 and 16.84% CO_2 in TOC and PPC pools, respectively, compared to control (no fertilizer) plots (Fig. 3b). The highest CO_2 sequestration (21.01 t ha^{-1}) rate in the APC pool was observed in VC + NPK plots, followed by FYM + NPK (18.23 t ha^{-1}) and GL + NPK (16.47 t ha^{-1}).

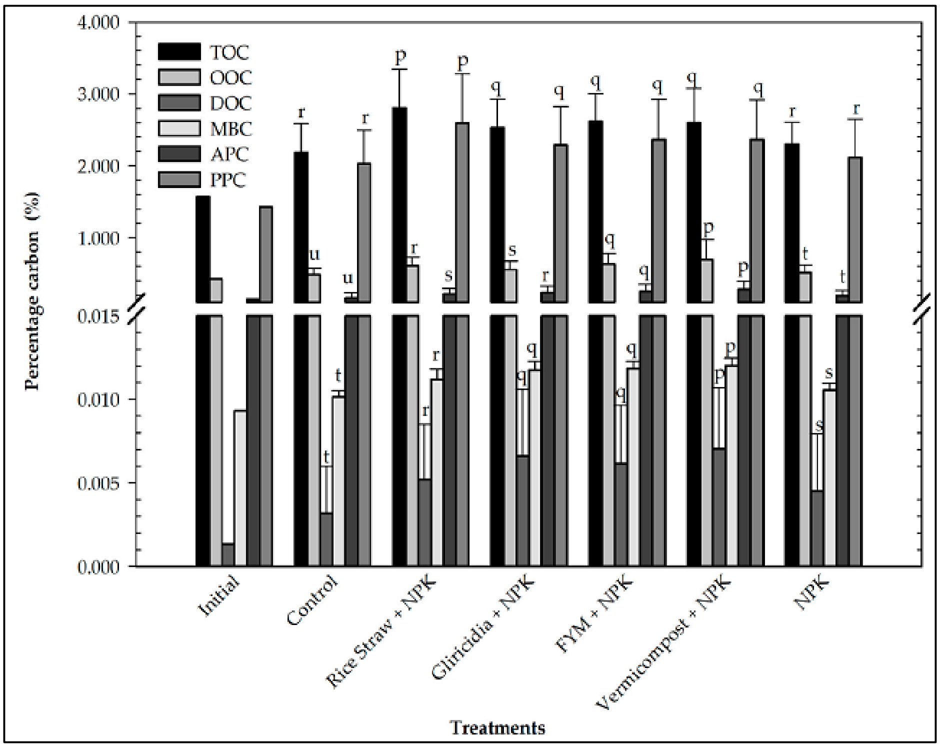

Fig 3a: Effects of treatments on different pools of organic carbon (%) in the rice rhizosphere soil [Source: Ghosh *et al*., 2021] [24]

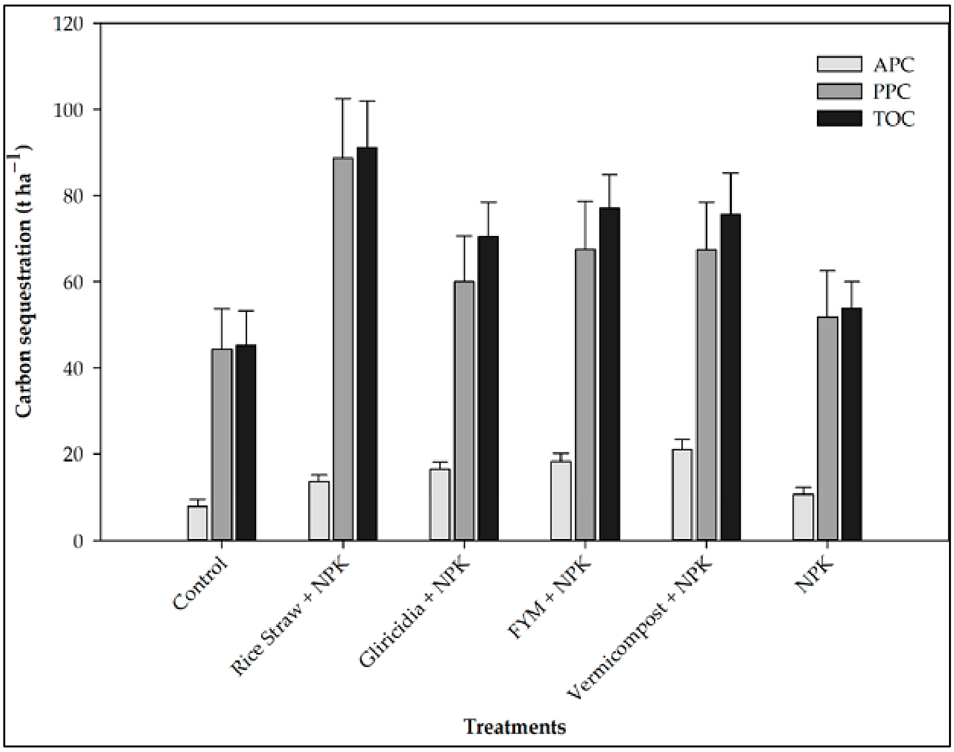

Fig 3b: Effects of treatments on carbon sequestration in terms of total organic carbon (TOC), passive pool of carbon (PPC) and active pool of carbon (APC) values [Source: Ghosh *et al*., 2021] [24]

Häring *et al.* (2017) also found that the continuous manure fertilization in FP plots significantly increased SOC stocks by 0.76 kg m^{-2} per year. Over two years, C input by manure was 2.4 kg m^{-2}. Interestingly, measured SOC increase was only slightly lower than the amount of applied manure-C. After 0.5 years, 89% and after two years 82% of the applied manure C were found in the SOC stocks of FP plots. After 1.5 years, SOC stocks of FP plots exceeded those of BC plots. SOC stocks in control plots were lowest, but slightly increased, similar to BC plots, beyond 0.5 years. Relative to the control, BC plots had only 31 ± 15% higher SOC stocks while FP had 64 ± 19% higher SOC stocks, after two years. Frequent tillage and the lack of organic fertilization further explain the observed SOC loss.

Samal *et al.* (2017) [45] reported that full CA recorded significantly higher TOC stock (47.71 ± 2.46 Mg C ha^{-1} soil) as compared to other scenarios in the total depth of soil studied. On the contrary, S_4 (diversified cropping system with high cropping intensity) showed significantly lower C stock (39.33 ± 2.40 Mg C ha^{-1}) than all other scenarios. On an average, TOC stock in different scenarios follows the order: S3 (47.71 ± 2.46) > S_2 (43.91 ± 0.84) > S_1 (41.65 ± 0.13) > S_4 (39.33 ± 2.40 Mg C ha^{-1} soil). Maximum accumulation of SOC (19.41 ± 1.84 Mg C ha^{-1}) in top depth of soil was observed under S3 followed by S_4 (16.56 ± 1.71 Mg C ha^{-1}), S_2 (16.53 ± 0.78 Mg C ha^{-1}) and S_1 (16.22 ± 0.60 Mg C ha^{-1}) and SOC accumulation reduced in lower depths. In 10–20 cm depth significantly low SOC was observed in S_4 (12.61 ± 0.10 Mg C ha^{-1}) and statistically at par values of SOC were obtained in rest scenarios (S_1–S_3). In 20–30 cm soil depth significantly greater SOC accumulation was recorded in S_2 (12.82 ± 1.10 Mg C ha^{-1}) and S^3 (13.10 ± 0.21 Mg C ha^{-1}) in comparison to S_1 (10.36 ± 1.07 Mg C ha^{-1}) and S4 (10.16 ± 0.80 Mg C ha^{-1}).

Naresh *et al*. (2018) [39] observed that the highest SOC stock of 72.2Mg C ha^{-1} was observed in F_6 with T_6 followed by that of 64Mg C ha^{-1} in F_4 with T_2 > that in F_3 with T_4 (57.9Mg C ha^{-1})> F_5 with T^1 (38.4Mg C ha^{-1}) = F_7 with T_5 (35.8Mg C ha^{-1}), and the lowest (19.9Mg C ha^{-1}) in F_1 with T_7. Relatively higher percentage increase of SOC stock was observed in F_6 with T_6 treatment (56.3Mg C ha^{-1}) followed by F_4 with T_2 (51.4Mg C ha^{-1}) and F_3 with T_1 (48.4Mg C ha^{-1}).

Potential Regulation of Soil Carbon Pool

Soil carbon stocks consist of soil organic carbon (SOC), soil inorganic carbon (SIC) and total carbon (TC). Soils contain carbon in both organic and inorganic forms, i.e., oxidized carbon and non-oxidized carbon. The sum of the two forms of carbon is referred to as total carbon. The global soil carbon, estimated to be 2500 Pg (1 Pg = 10^{15} g) which is nearly 3.3 times the atmospheric pool and 4.5 times the biotic pool size (760 Pg) (Lal, 2010) whereas, the total amount of SOC and SIC stored worldwide are estimated to be 1550 Pg C 950 Pg in the top 1 m of soils in a dynamic equilibrium of gains and losses (Fig. 4).

Naresh *et al*. (2018) [39] also found that the Highest carbon sequestration potential change (88.2%) was found in T_3 zero tillage with 6tha^{-1} residue retained plots followed by T_2 zero tillage with 4tha^{-1} residue retained plots (84.7%) and T_6 permanent raised beds with 6tha^{-1} residue retained plots (80.1). The use of T_1 zero tillage without residue retained and T_4 permanent raised beds without residue retained for sixteen crop cycle increased carbon sequestration potential by 24.4% and 23.1% more than that of T_7 conventional tillage, respectively. The final SOC concentrations in both NPK and NPK+FYM treatments were higher than the control treatment. Compared to the NPK treatment also, the NPK+FYM treatment had higher SOC concentration in all the nutrient management practices. The highest increase in SOC in the 50% NPK by CF+50% NPK by FYM treatment was observed. However, quantities of SOC at the 0-400 kg of soil m^{-2} interval decreased under T_1, T_4 and T_7 treatments evaluated. Stocks of SOC in the top 400 kg of soil m^{-2} decreased from 7.46 to 7.15 kg of C m^{-2} represented a change of -0.31 ±0.03 kg of C m^{-2} in T1, 8.81 to 8.75 kg of C m^{-2} represented a change of - 0.06 ±0.05 kg of C m^{-2} in T_4, and 5.92 to 5.22 of C m^{-2} represented a change of -0.70 ±0.09 kg of C m^{-2} in T_7 between 2000 and 2018.

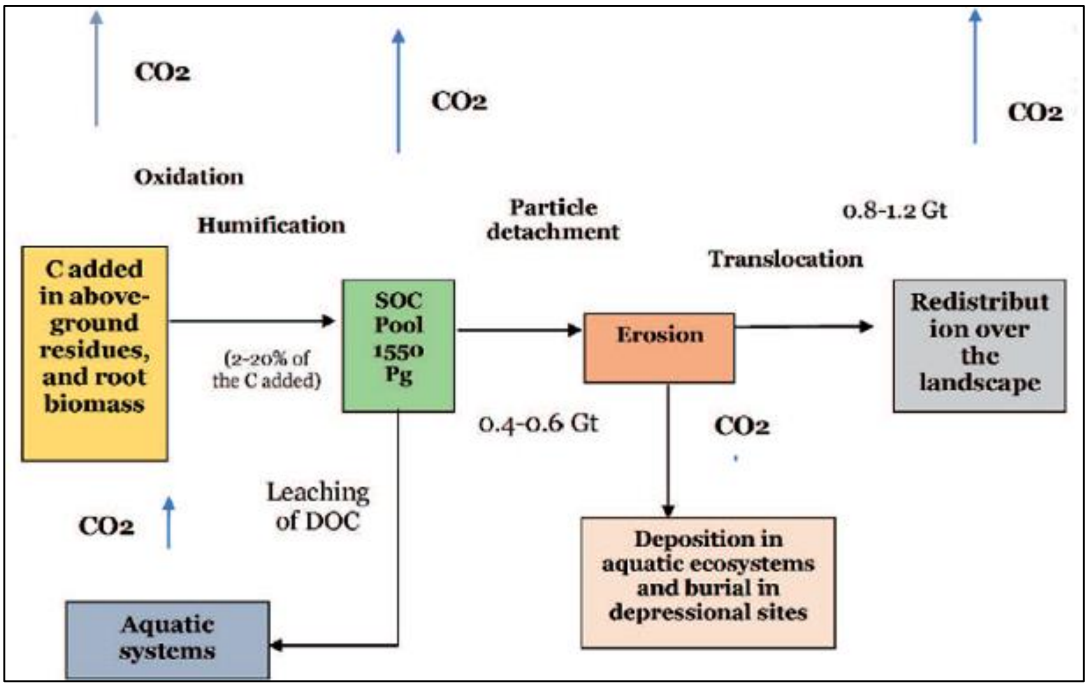

Fig 4: Soil organic carbon dynamic equilibrium [Source: Lal, 2004] [32]

Pools of C in rocks are inert and changes over the millions of years of time while pools of C in the terrestrial biosphere, atmosphere, and oceans constitute active pools that are vulnerable to anthropogenic activities. Exchange of C among these pools over a short and long period of time is known as the Global Carbon Cycle (GCC). The Global Carbon Cycle has been changing due to the increase in atmospheric C pool and decrease in biosphere and soil C pool consequently resulting in global warming.

Conversion of natural to agricultural ecosystems causes 60% depletion of the SOC pool of temperate regions and 75% or more in cultivated soils of the tropics, and further creates severe soil degradation when the output of C exceeds the input.

By improving farming techniques to increase SOC, e.g., no till, mulching, and crop rotation the addition of human-made artificial carbon materials (ACM) received considerable attention, due to the potential sustainability and stability of the sequestered C. Overall; metabolic engineering modified microbes can be regarded as potentially effective to mitigate global climate change. However, the performance of such manipulated organisms in real soil is still to be analyzed, and their sustainability and competitiveness with the natural poly-type and potential side effects, especially in arable soils, are to be most carefully examined.

Hagemann *et al*. (2007) [27] reported that GHG emissions should be counter-balanced by a yearly increase of global soil carbon stocks in the top 40 cm of soils by 0.4% considerably. Moreover, agricultural activities and land-use change may enhance GHGs emissions like 25% of the CO_2, 50% of the CH_4, and 70% of the N_2O that perhaps compensate by SOC sequestration. The average SOC sequestration rate (up to 30 cm depth) under ZT was 0.57 ± 0.13 Mg C ha^{-1} yr^{-1} (West and Post, 2002). However, the adoption of ZT practices enhances the physical protection of SOC where soil bulk density is relatively high because the volume of small macro-pores (15–150 μm) gets reduced which is important for microbial activity.

Tang *et al*. (2022) [54] revealed that added up to 0.03 wt% C of an artificial humic or fulvic acid (A-HA and A-FA) to soil for improving soil texture and analyzed their influence on typical soil parameters (Fig.5a) and total organic carbon content of the soil increased by up to 2.1 wt% (compared to the added 0.03 wt% C).

Cheng *et al*. (2018) [16] found that Soil organic carbon stocks (0-20 cm) declined in the control (33.6 tha^{-1}), N (33.5 tha^{-1}) and NP (34.7 tha^{-1}) treatments in contrast to the initial organic carbon stock (38.0 tha^{-1}), whereas the organic carbon stocks ascended in the NPK (39.1 tha^{-1}) and appended manure treatments (41.8-44.5 tha^{-1}) in the topsoil during thirty-three years periods. Soil organic carbon sequestration rates (0 - 20 cm) in the MN (0.12 $tha^{-1}yr^{-1}$), MNP (0.18 $tha^{-1}yr^{-1}$), MNPK (0.20 $tha^{-1}yr^{-1}$) and hMNPK (0.19 $tha^{-1}yr^{-1}$) treatments were significantly higher than those in M (0.12 $tha^{-1}yr^{-1}$) and NPK (0.03 $tha^{-1}yr^{-1}$) treatments, and the sequestration rate in the M treatment was significantly higher than that in the NPK treatment.

Soil organic carbon sequestration was mainly influenced by climates, soil types, tillage, fallows, rotations, fertilizations, and so on. Zhang *et al*. (2010) [61] reported that the organic carbon conversion rate decreased significantly with the increase in the annual active accumulative temperature and precipitation. Under normal conditions, the soil organic carbon accumulation rate tends to decrease with the higher soil temperature and moisture. There was usually a positive linear correlation between soil organic carbon levels and soil clay contents of surface soils (Gami *et al*., 2009; Naresh *et al*., 2020) [23, 51]. No-tillage could increase the soil organic carbon stock compared with conventional tillage, because it could significantly reduce soil carbon release by reducing the turnover of soil aggregates and the exposure of young and labile organic matters to microbe decomposition (Yan *et al*., 2007; Naresh *et al*., 2018) [39], which had been considered as an effective and environment friendly soil carbon sequestration strategy (Lal, 2004) [32]. The crop straw return to soil significantly increased soil carbon stocks (Xu *et al*., 2011; Wang *et al*., 2018) [57].

Buss *et al*. (2021) observed that nutrient leaching and low nutrient use efficiency in agricultural systems (Fig. 5b) are significant environmental and economic issues. SOC has a very high cation exchange capacity (CEC), so that building up SOC helps to retain positively charged nutrients, such as Ca, Mg and K. Biochar and basalt application mainly affect the CEC in acidic soils through an increase in soil pH, although the direct provision of negatively charged surface sites may also have a positive influence (Anda *et al*., 2015) [3]. Enrichment of biomass with inorganic nutrients before pyrolysis or application of biochar with nutrient-rich organic or inorganic materials offers slow-nutrient release potential that provides synergistic improvements on plant growth (Hagemann *et al*., 2017) [27]. Plants and microorganisms can mine nutrients from basalt and hence increase nutrient availability and basalt weathering rates by exudation of organic ligands, such as acetate and propionate (Kantola *et al*., 2017) [31].

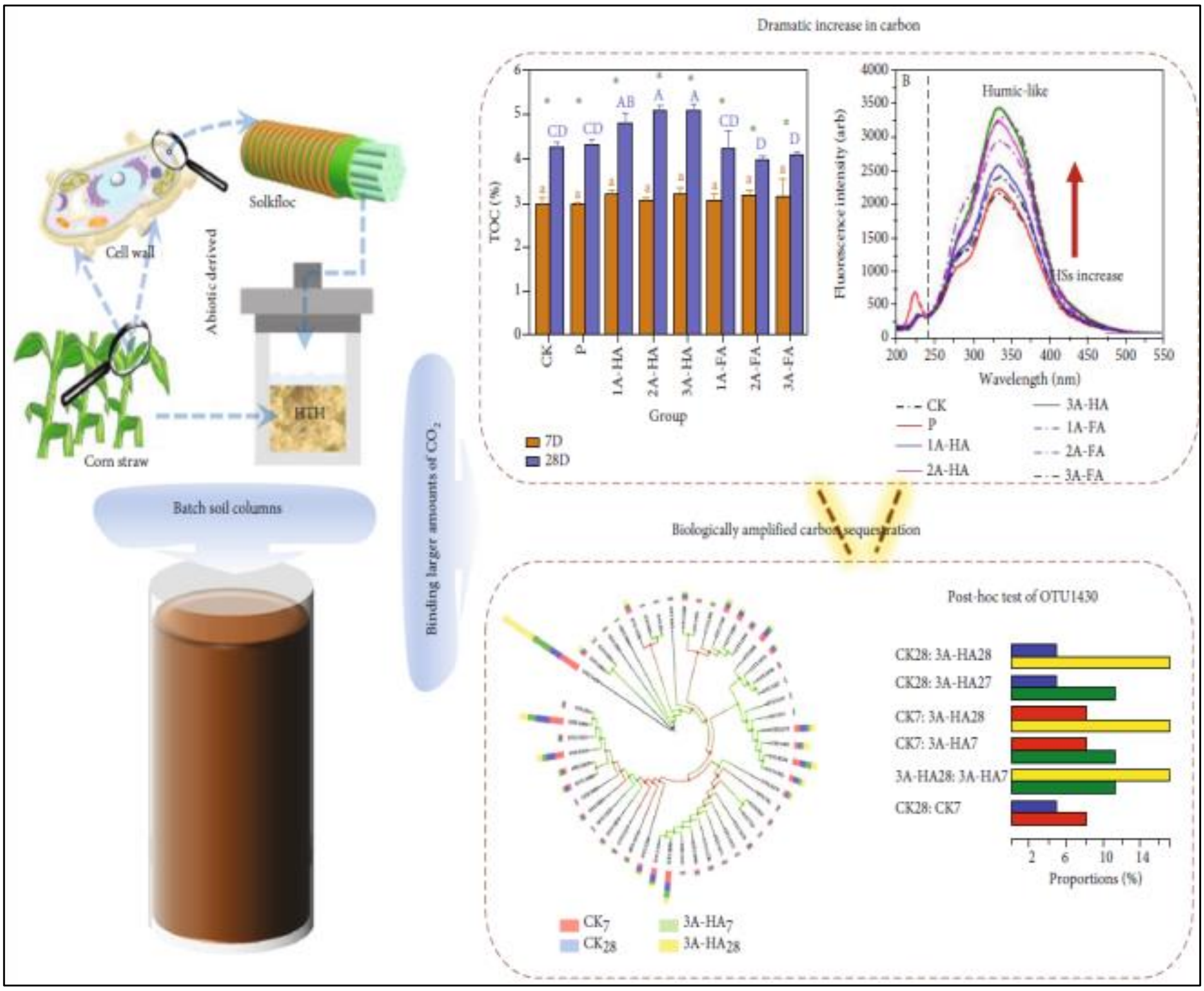

Fig 5a: Artificial humic substances improve microbial activity for binding CO_2 [Source: Tang *et al*., 2022] [54]

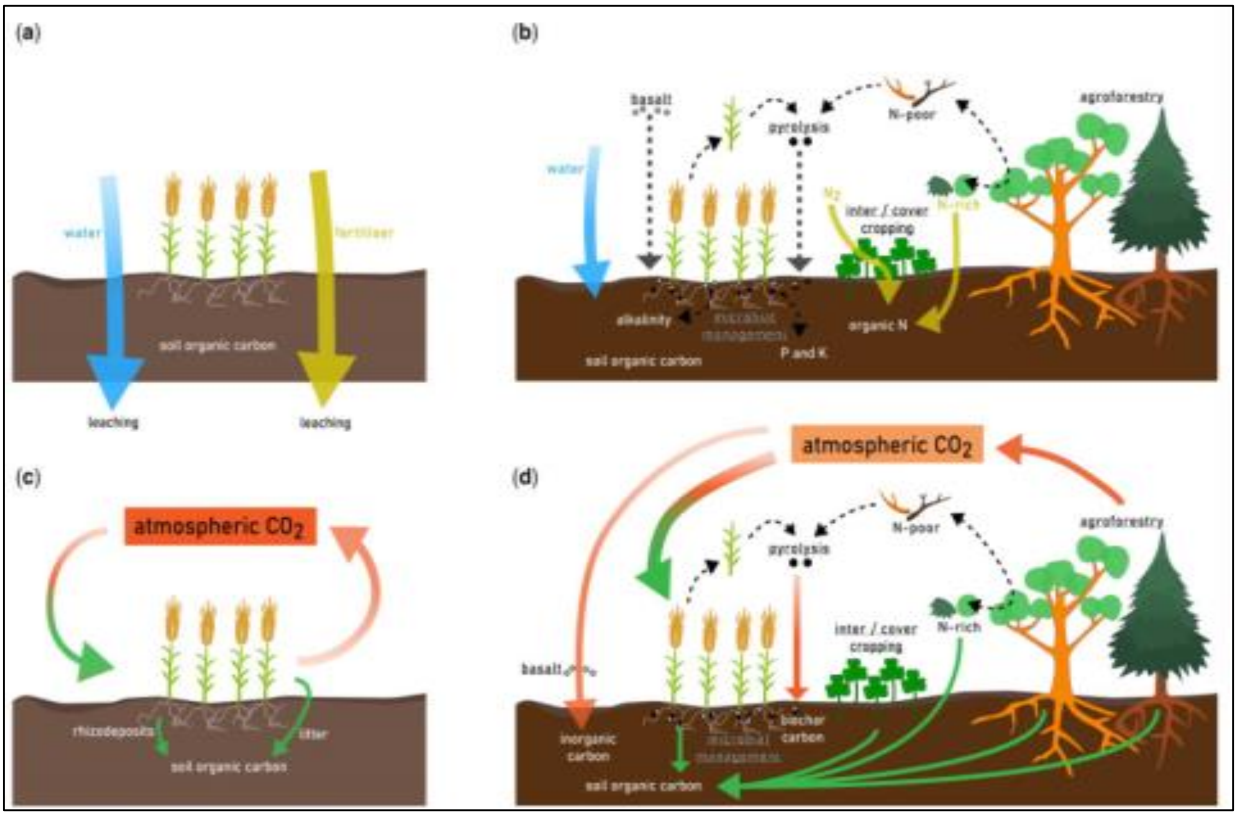

Fig 5b: Nutrient and water (a, b) and carbon dynamics (c, d) in agro-ecosystems [Source: Buss *et al*., 2021]

Ghosh *et al.* (2021) [24] revealed that the initial pool-I, pool-II, pool-III and pool-IV C contents of soil accounted for 4.46%, 4.39%, 18.41% and 72.74%, respectively, of the total C (1.57%). Application of organic manures significantly increased the concentrations of these pools in the rhizosphere soil. Accordingly, the greatest increases in pool-I (62.4%), pool-II (100.2%) and pool-III (26.1%) C contents were observed in VC + NPK plots, whereas pool-IV C was the highest (29.3%) in RS + NPK plots. Further, significant increases in oxidizable carbon pools were observed for other organic manures (except for pool-III of GL + NPK plots) compared to control. The lowest increases were observed in chemical-fertilizer-treated plots for pool-I (6.5%), pool-II (38.1%) and pool-IV (5.2%) C contents over the control. The initial active and passive pools of C in soil accounted for 8.85% and 91.15%, respectively, of the TOC content (1.57%). However, there were significant changes in the active and passive pools of C with the application of organic manures. Among the organic manures, VC + NPK plots had the greatest increase (100.21%) of active pool C, followed by FYM + NPK (81.33%), GL + NPK (70.74%) and RS + NPK (53.62%) plots.

Sapkota *et al.* (2017) [46] revealed that the effects on SOC stock were significant at 0–0.05 and 0.05–0.15 m soil depths only. At 0–0.05 m, ZTDSR-ZTW+R and PBDSR-PBW+R, on an average, had significantly higher SOC stocks, that is 2.4 t/ha more than CTR-CTW. ZTDSR-ZTW, ZTDSR-ZTW+R and PBDSRPBW+ R had a similar improvement in total SOC at 0.05–0.15 m, which was significantly higher (by about 2.0 t/ha) than for CTR-CTW. All the treatments had similar SOC stocks at 0.15–0.3 m and 0.3–0.6 m soil depths. Calculations for the whole 0–0.6 m depth showed that ZTDSR-ZTW+R and PBDSRPBW+ R contained 5.6 t and 3.9 t/ha more SOC than CTR-CTW, respectively.

Naresh *et al.* (2018) [39] showed that, soil organic carbon buildup was affected significantly by tillage and residue level in upper depth of 0- 15 cm but not in lower depth of 15-30 cm. Higher SOC content of 19.44 g kg^{-1} of soil was found in zero tilled residue retained plots followed by 18.53 g kg^{-1} in permanently raised bed with residue retained plots. Whereas, the lowest level of SOC content of 15.86 g kg^{-1} of soil were found in puddle transplanted rice followed by wheat planted under conventionally tilled plots.

Soil ecosystem services

Soil ecosystem services depend on soil properties that are the basis for soil functionality and they are affected by soil management practices (Adhikari and Hartemink, 2016). Soil ecosystem that soil properties support the performances of soil functions with effects on soil ecosystem services such as carbon sequestration, nutrient cycling and capacity, food, soil biodiversity, and primary production. Tang *et al.* (2022) [54] also found that A-HA plays a central role in regulating carbon sequestration bacterial community structure to amplify carbon sequestration efficiency and organizing cascades and exchange by the "currency" of microbial patches that are buffered electron-proton pairs (Fig. 6a). Artificial humic substance (A-HS), with no doubt, is capable of promoting microbe growth, creating excellent habitats for soil microbes and providing available nutrients and A-HS can play a central role in stabilizing carbon pools in soil.

Gogoi *et al.* (2021) [25] reported that the most sustainable treatments have resulted in T_3, T_5 and T_7, highlighted in Fig. 6b, because of higher levels in terms of the yield of crops, soil microbial biomass carbon and microbial count, and enzymatic activity. Therefore, this gives management practices a crucial responsibility in enhancing ecosystem services. This research has attempted to indicate as a first approximation which integrated nutrient management could be more effective to foster the soil ecosystem services in rice-wheat cultivation.

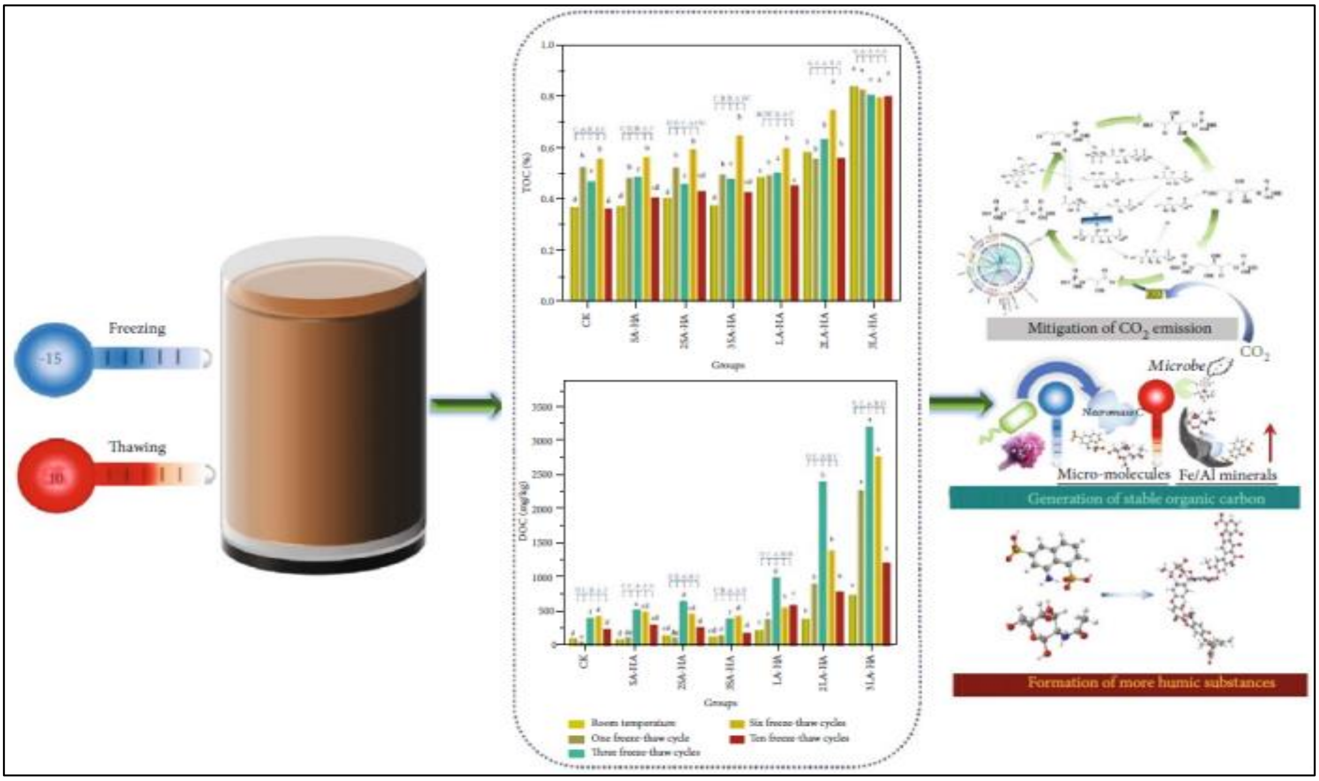

Fig 6a: Artificial humic acid biologically amplifies carbon sequestration [Source: Tang *et al*., 2022] [54]

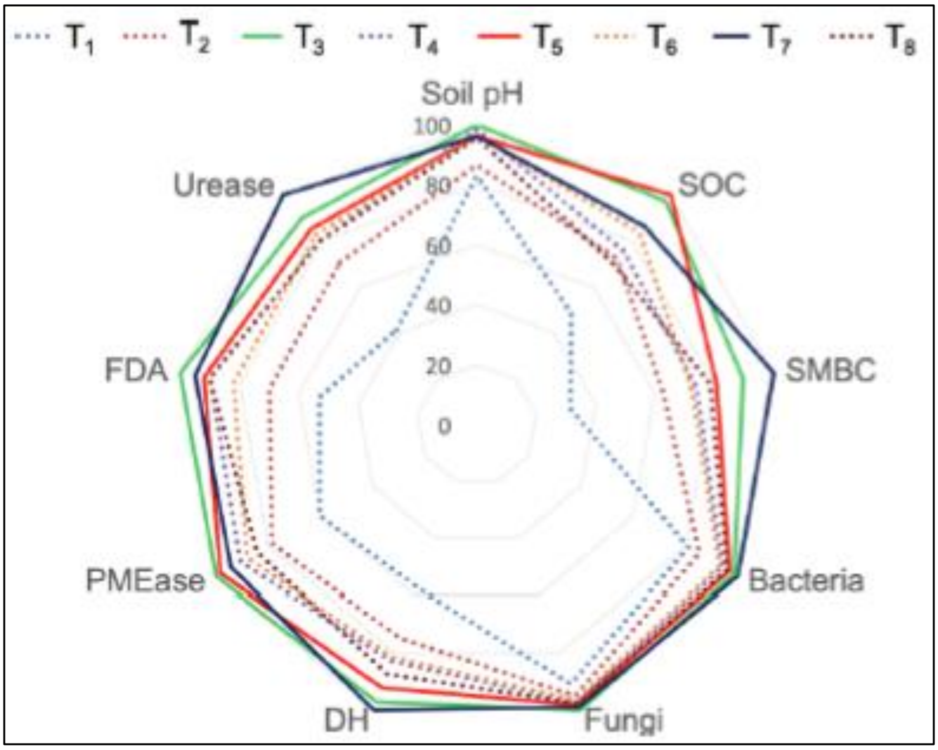

Fig 6b: Effect of integrated nutrient management on soil properties including the soil biota [Source: Gogoi *et al*., 2021] [25]

Naresh *et al*. (2018) [39] revealed that the soil reductase, urease and invertase enzyme activities decreased in the T_1, T_4 and T_7 treatments, and increased in the T_2, T_3, T_5 and T_6. The soil enzyme activity showed that the treatments T_5 and T_6 comprised with the increase of continuous residue retention in rice-wheat cropping years, the differences of enzyme activity was more significant. Continuous cropping 18 years, the similarity of enzyme activities was 46.4%, much more than that of T_7. The other group comprised only ZT (T_1) and PRB (T_4) without residue retention, with a similarity to other groups of less than 25.4%. This result indicated that the diversity of the enzyme activity was altered to a greater extent than the bacterial by continuous rice-wheat cropping system.

Nazir *et al*. (2021) reported that Soil alkaline phosphatase activity in rice-residue removing and rice-residue burning treatments were decreased by 2.66 and 4.31%, respectively. However, fertilizer application, green manuring, farmyard manure application, rice-residue incorporation and rice-residue mulching increased soil alkaline phosphatase activity by 0.05, 2.98, 1.51, 5.19 and 3.75%, respectively. The rice-residue removing and rice-residue burning treatments decreased the dehydrogenase activity of soil by 1.84 and 14.51%, respectively (Fig.7). However, fertilizer application, green manuring, farmyard manure application, rice-residue incorporation and rice-residue mulching increased dehydrogenase activity of soil by 1.58, 3.80, 4.00, 13.76 and 3.96%, respectively. Soil urease activity following fertilizer application, rice residue removing and rice-residue burning treatments were decreased by 4.95, 9.59 and 7.37%, respectively. However, green manuring, farmyard manure application, rice-residue incorporation and rice-residue mulching increased urease activity of soil by 3.38, 5.39, 8.82 and 5.41%, respectively. However, for soil invertase activity, fertilizer application, rice-residue removing and rice-residue burning decreased the invertase activity of soil by 1.08, 1.09 and 8.99%, respectively. Invertase activity of soil following green manuring, farmyard manure application, rice-residue incorporation and rice-residue mulching treatments was increased by 4.44, 6.00, 15.22 and 8.43%, respectively. Soil catalase activity following fertilizer application, rice-residue removing and rice-residue burning treatments was decreased by 6.16, 2.58 and 8.05%, respectively. However, catalase activity of soil following green manuring, farmyard manure application, rice-residue incorporation and rice-residue mulching treatments was increased by 3.90, 2.17, 7.49 and 6.76%, respectively.

Foster *et al*. (2020) [22] reported similar findings for C-cyclase enzymes, which are also related to the colocalization and stability of C substances and enzymes on the surface of rice residues. Since the application of crop residues accelerates N mineralization, an increase in N-cycling enzyme activity occurs (Jing *et al*., 2020) [29]. The highest activity of phosphatase among the three rice-straw modifications (incorporation, removal and mulching) varied with the rice growing season and was different from patterns of invertase and urease activity. Similarly, alkaline phosphatase activity may be affected by many factors, such as soil pH and soil moisture (Chen *et al*., 2021). Criquet *et al*. (2004) [18] confirmed that phosphatases may be generated by bacteria or other microorganisms. However, due to the interference of high levels of phosphatase activity originating from roots, it is difficult to study the kinetics of microbial phosphatase production in soil. Soil organic carbon (SOC) sequestration significantly contributes to the improvement of soil fertility (Reddy *et al*., 2017) [44]. Accumulation of SOM in soil is a reversible process, and the intensive rice–wheat cropping system is responsible for its reduction in agro-ecosystems (Ayyam *et al*., 2019) [4]. However, this reduction in the concentration of SOM can be compensated for by the incorporation of different crop residues in soil, which help soils to regain their lost fertility (Shahbaz *et al*., 2017) [50].

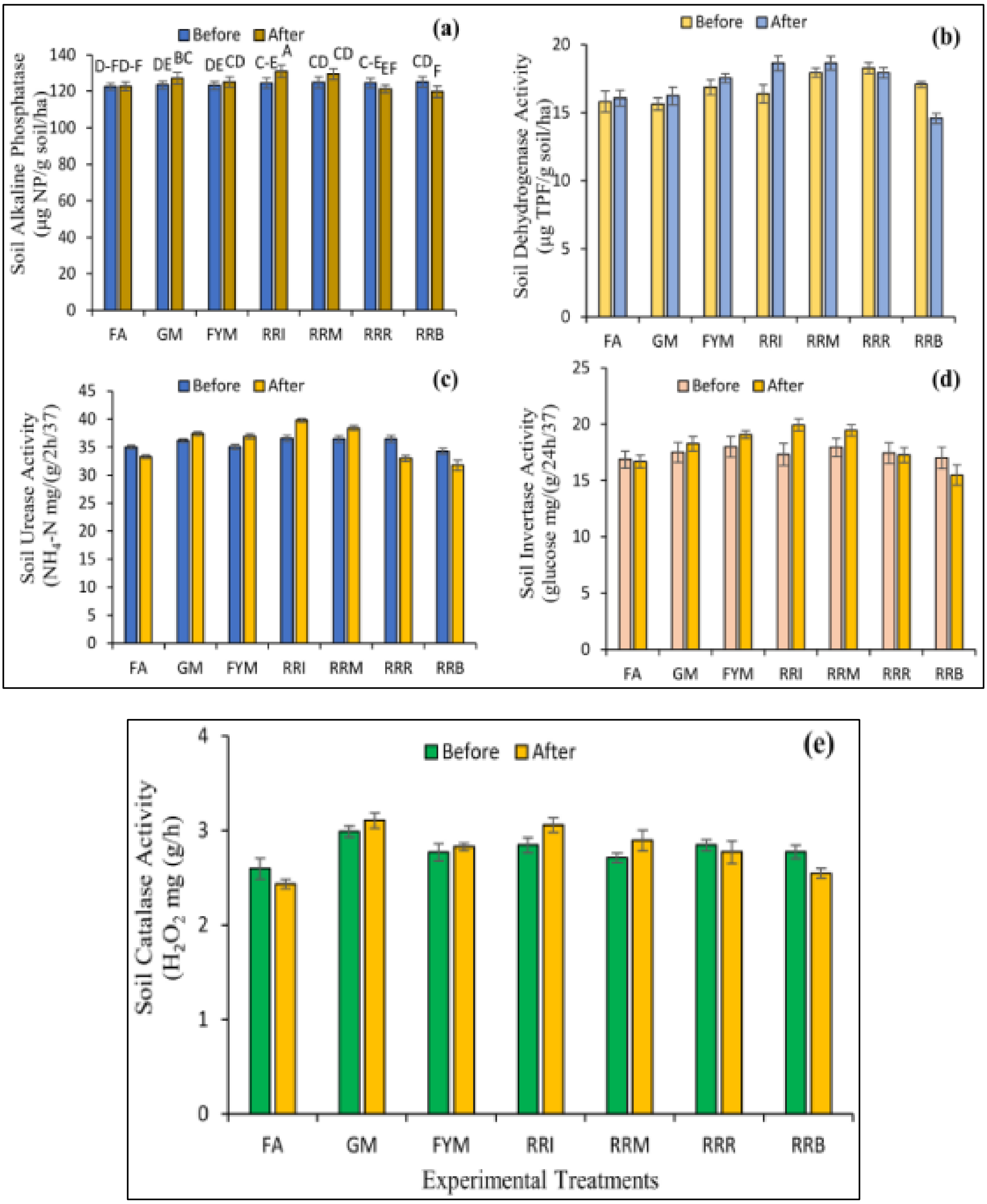

Fig 7: Effect of diverse farming approaches on the enzymatic attributes [soil alkaline phosphatase (a), soil dehydrogenase activity (b), soil urease activity (c), soil invertase activity (d), and soil catalase activity (e)] of soil samples by fertilizer application (FA); green manuring (GM); farmyard manure application (FYM); rice-residue incorporation (RRI); rice-residue mulching (RRM); rice-residue removing (RRR) and rice-residue burning (RRB) [Source: Nazir *et al*., 2021] [40]

Nazir *et al*. (2021) [40] also found that rice residues increased soil invertase activity more than the fertilizer-alone treatments, which is consistent with changes in SOC. Therefore, we hypothesize that soil enzymatic activities increase with the higher SOC caused by residue incorporation (Fig. 8). Fertilizer application, rice-residue removal and rice-residue burning decreased the enzymatic attributes. However, rice residue incorporation, FYM and green manuring practices improved soil enzymatic attributes. The observed increase in enzymatic activities due to green manure and FYM amendments is in accordance with previous studies (Goyal *et al*., 1993; Mikhailouskaya and Bogdevitch, 2009) [26, 37]. A possible mechanism by which crop-residue incorporation affects soil enzymatic activities is by changing the physicochemical characteristics of soil to influence soil enzyme activity.

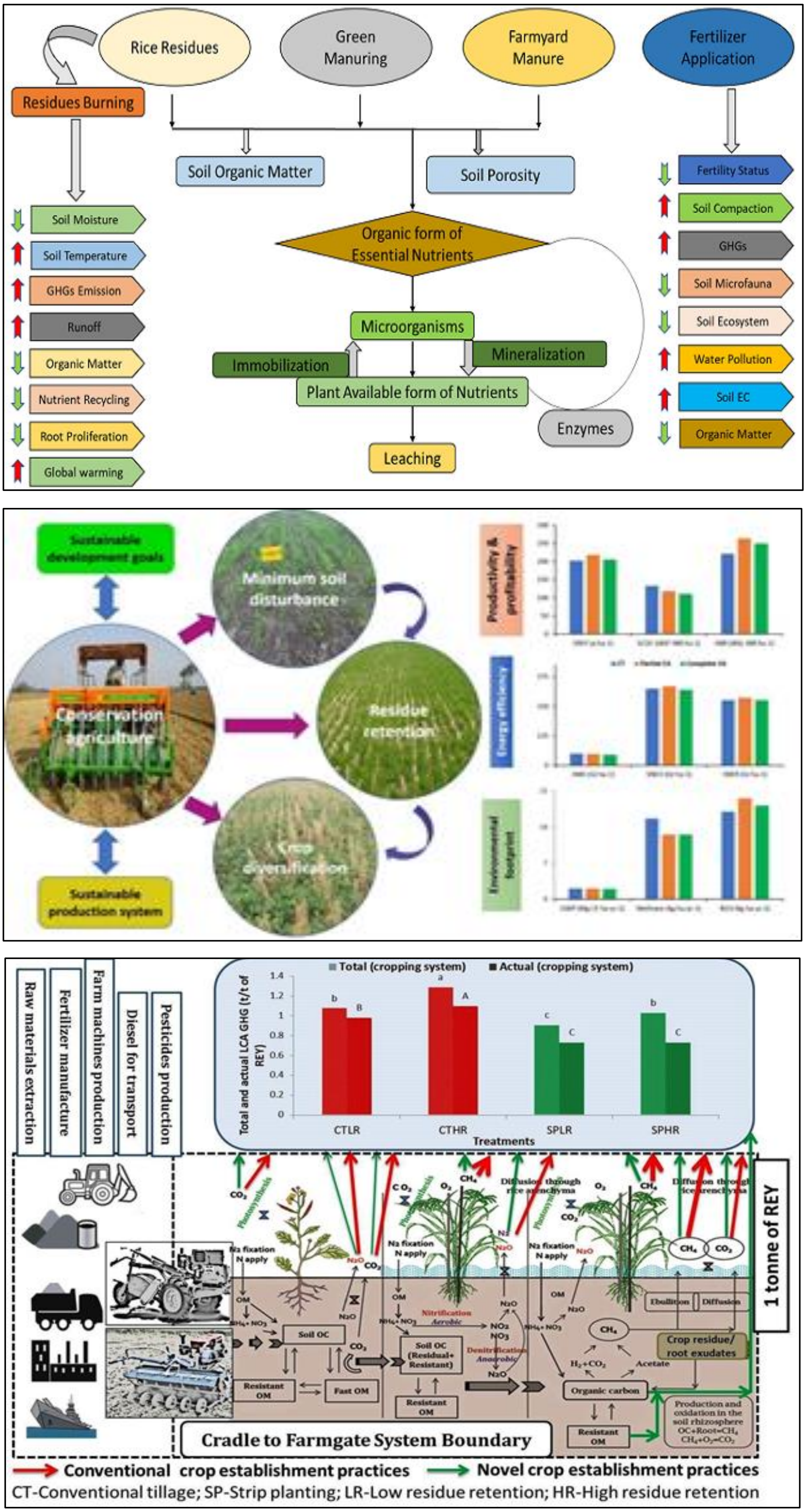

Fig 8: Rice-residue management interventions along with organic manures such as farmyard manure and green manure improves soil physicochemical, biological and enzymatic conditions [*Source*: Nazir *et al*., 2021] [40]

Adoption of conservation agriculture (CA) either in full or partial increased the system productivity (2-7%) and net returns (13-19%) and reduced the cost of cultivation (11-16%), energy input (5-10%), methane emission (20%) and overall global warming potential (1-7%) in comparison to conventional tillage (CT) production system under irrigated system (Mishra *et al*., 2021) [36].

Conclusions

Conservation agriculture minimizes C loss from the soil and helps in C restoration to manage agroecology with sustained productivity. Conservation tillage in association with suitable management practices, depending upon climatic conditions, enhances SOC content efficiently under NWIGP environments. Moreover, straw incorporation can lead to improving C sink in upland soils and decreases fluxes of GHGs like CH_4. However, manuring and fertilization increase crop biomass carbon, organic carbon input; however, only organic manure application can increase soil organic carbon concentration in the rice-wheat cropping system of China. Averagely, crop biomass carbon is increased by 39.9 - 77.2% compared to unfertilized control due to organic manure or chemical fertilizer application. Total organic carbon input into soil is increased by 10.2 - 23.3 kg C ha^{-1} yr^{-1} due to manuring or fertilization. Soil organic carbon concentration in the topsoil has decreasing tendency in the control, N and NP treatments; however, soil organic carbon concentration has ascending tendency in the NPK treatment and is significantly increased in the manure alone or manure appended chemical fertilizer treatments. However, organic manure application or integrated organic manure with chemical fertilizer application can be important strategies for increasing soil organic carbon sequestration and maintaining soil quality in the rice-wheat cropping system of NWIGP.

Soil CS and crop production is a better, economical and reliable option because it captures C as well as grows plants which provide food to us. C sequestration in crop lands and rangelands requires certain amounts of organic matter (OM) presence in the soil called soil organic matter (SOM). Organic amendments like animal and poultry manures, the incorporation of different crop residues, different types of compost and good agricultural practices like cover crops, nutrient management, mulching, zero and no-tillage techniques, soil biota management and mulching are effectively used for this purpose. These enhance the soil organic matter and improve the soil's physical and chemical properties that help to sequester more C in the soil, which ultimately contributes towards CS and CC mitigation.

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