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Sustainable Carbon Management Practices (CMP) - A Way Forward in Reducing CO₂ Flux

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Abstract

Asian agriculture sector contributes about 44% of greenhouse gas (GHG) emission. Predominantly paddy rice cultivation couples with indiscriminate use of agrochemicals, burning of fossil fuels in farm machinery majorly causes GHG emissions from farmlands in Asia. Presently, Asian soils have 25% cropland soil organic carbon (SOC) content but with moderately to highly vulnerability towards land degradation. To make up the soil carbon losses which has occurred due to continuous cultivation and tillage, it is recommended to adopt suitable carbon management practices to sequester carbon in soil through their physio-chemical protection. Conservation agriculture (CA), cover crop, crop diversification, integrated nutrient management (INM) and balanced fertilisation promotes better soil structure formation, stabilisation of aggregate associated carbon, microbial polymerisation of organic matter as well as a better root architecture. Carbon management practices not only improve soil fertility but also supports improved grain and straw yield. More the yield more biomass addition occurs to the soil. Soil carbon sequestration may not be the only panacea of climate change related issues, but is certainly a way forward to enriched soil fertility, improved agronomic production as well as adaptive- mitigation for offsetting anthropogenic GHG emission.

Keywords: GHG, Paddy rice, CA, INM, Microbial polymerisation, Adaptive mitigation

1. Introduction

The ever-increasing population growth of the world has resulted in putting more and more pressure on a piece of arable land demanding higher and higher production. The world statistics shows reduction of per capita arable land from 0.23 ha in 2000 to 0.19 ha in 2015. While the per capita arable land in North America is still 0.55 ha, the numbers for South Asia and East Asia- Pacific are 0.12 ha and 0.11 ha respectively (5–6 times lower than that of North America) [1]. The shrinkage of arable land compels the farmers to go for over dose of fertiliser application which is a main source of many kind of pollutions and emission. Food sector contributes to around quarters (26%) of the global greenhouse gas (GHG) emission out of which solely crop production practices cause **27% emission share of food sector**. The fields associated with food sector in Asian countries are also under threat as the current situation of vulnerability and their less reliance to changes are affecting their ecosystem function and services.

Sub-region	Food and fibre	Biodiversity	Land degradation
North Asia	Moderately resilient	Highly vulnerable	Moderately vulnerable
Central and West Asia	Highly vulnerable	Moderately vulnerable	Highly vulnerable
Tibetan Plateau	Moderately resilient	Highly vulnerable	Moderately vulnerable
East Asia	Highly vulnerable	Highly vulnerable	Highly vulnerable
South Asia	Highly vulnerable	Highly vulnerable	Highly vulnerable
South east Asia	Highly vulnerable	Highly vulnerable	Highly vulnerable

Table 1.
Sectoral vulnerability in food, land and biodegradation in sub-continent of Asia.

The food, biodiversity and land degradation condition in every sub-section of Asia are moderately to highly vulnerable and less resilient [2] which has a gradual effect on climate change. Before we get caught in catastrophic climate change impact, required management practices are to be adopted (**Table 1**).

2. Scene of Asian agriculture in GHG emission and carbon storage potential

According to IPCC (Intergovernmental Panel on Climate Change) 2014 [3] record, the scenario of GHG emission is very critical in Asia as Asian agriculture causes an average of 44% of global agricultural GHG emission (**Table 2**).

The agricultural GHG emission contributors such as enteric fermentation and paddy rice cultivation are the major source of methane emission whereas the major sources of nitrous oxide emission are application of manures and fertilisers. The worldwide contribution of paddy rice cultivation towards GHG emission (CH₄) is 11%. For higher crop production farmers rely on synthetic fertiliser application which is a rapidly growing source of emission having the increase rate of around 37% since 2001 [5]. Along with that the use of large number of machineries are the source of CO₂ emission due to burning of fossil fuel. The imbalanced fertilisation is another reason for the release of soil carbon to the atmosphere (**Figure 1**).

To meet the daily food requirements, the agricultural stakeholders must make two kind of assessments in order to understand the impact of climate change on food and crop production i.e., mitigation and adaptation. Mitigation will reduce the emission of GHG from agricultural sources whereas adaptation will enable the agricultural sectors to perform well in the existing climate change situation through modified management and production systems. Both the approaches can be regulated through various policies e.g., ensuring the economic value of carbon and its sequestration will be an important development in the agriculture sector [7]. The adaptive-mitigation techniques to capture carbon in soil in organic form is a potential factor for controlling CO₂ emission as well as a factor for improving soil quality and health.

Carbon pool	Carbon changes		Rate of carbon increase in the atmosphere
	Fossil fuel use	Land Use	
750 Gt	+ 5.5 Gt yr. ⁻¹	+1.6 Gt yr. ⁻¹	+3.3 Gt yr. ⁻¹

Table 2.
Carbon pool size and changes due to human activities [4].

Figure 1.
Contribution of various agricultural sectors towards GHG emission in Asia. See [6].

Carbon storage in terrestrial system is important as soil can hold three times more carbon than vegetations that they support. The Soil carbon pool which is the largest reactive carbon in terrestrial ecosystem [8], is estimated to be 2500 Pg (10^{15}) up to 1 mt depth, of which soil organic carbon is about 1500 Pg. This stock accounts for about 3.2 times the size of atmospheric carbon pool and 4 times that of biotic pool [6, 9]. Thus, capturing the carbon from agricultural lands in stable form can reduce CO₂ content of the atmosphere.

Again, the global distribution of carbon and its storage potential is highly influenced by climatic conditions such as temperature and precipitation [10]. The higher decomposition rate controlled by higher oxidation of organic matter result in lower Soil Organic Carbon (SOC) in the tropics as compared to higher SOC of cooler regions. Though all the parts of Asian croplands contain moderate amount of carbon, and all together they account for about 25% of global cropland carbon [11]. But the regions of South Asia with low level of SOC and with serious degradation problems are global highest in carbon storage per hectare basis (0.62–1.28 t C/ha/yr) over 2.9 million km² of land which all together turns out to be 2.2 to 4.5 Pg C storage/yr. in South Asia [11]. Thus, the management practices which are proved to be potential drivers of SOC enrichment must be encouraged as mitigative measure in agricultural soils.

3. Understanding role of SOC and carbon management practices

Soil Organic carbon (SOC) is the controlling factor for soils physical, chemical, biological and ecological functionality and wellbeing. Not only soil's health and productive capacity but soil carbon can also mitigate hazardous climate change. Quality and quantity of SOC; its dynamics/turnover is the main governing factor of soils ecosystem functions. A huge loss (50 to 75% and with magnitude of loss of around 30 to 60 Mg C/ha) of antecedent soil C pool has occurred due to land conversion, cultivation and erosion associated with it in most agricultural ecosystems [12]. Generally, agricultural soils contain considerably less SOC than soils under natural vegetation, hence, these lands are deprived of C than their ecological potential.

Carbon management practices (CMP) aim to sequester i.e., to capture and secure storage of carbon that would otherwise be emitted to, or remain, in the atmosphere. In other words, CMP is enhancing and/or maintaining soil carbon

Attributes	Mechanism
Physical stability	Depth distribution, Aggregate stabilisation, Organic macromolecules.
Chemical recalcitrance	Charred materials, Interaction with cations, Hydrophobicity, Complexation with clay minerals, intermolecular interaction.
Biotic mechanisms	Recalcitrant fractions, Structural composition, Condensation reaction.

Table 3.
Mechanism of increasing MRT of SOC for its stabilisation.

not allowing it to escape out to the atmosphere. In agricultural fields, addition of biomass carbon and organic manure is a direct approach but stabilisation of the soil carbon is through its physico-chemical property. Physical mechanism includes formation of organo-mineral complexes, encapsulation in microaggregates within macroaggregates, deeper placement of carbon in the soil profile away from natural and anthropogenic perturbation zone [12]. At the same time, the producer must seek for those practices which will promote sequestration of SOC in croplands without compromising the provision of ecosystem services such as food, fodder, fibre or other agricultural products. Thus, it is very crucial to understand the mechanism of carbon stabilisation by improving the mean residence time (MRT) and by offsetting anthropogenic emissions [13] which is vary according to the climatic condition and soil properties and also on existing soil carbon content of the particular region. For example, the same management practice which are proved to increase SOC can result in high amount of loss and unintended consequences in those soils which are already saturated with organic carbon [14] (**Table 3**).

4. Carbon management practices (CMP)

A 4% increase in global agricultural soil carbon pool up to 1 m depth, 2–3 Gt C can be sequestered annually which would drawdown global anthropogenic GHG emission by 20–35% [15] but practicality has many constraints. For example, in countries with low (inherent) SOC like India, high rate of decomposition due to high temperature and the removal of crop residues does not allow this concept to work well [16]. Due to a greater surface area and charge density, organic matter can react with soil particles to form organo-mineral complexes. The mean residence time of carbon fractions are functions of their turnover rate which is dependent on the degree of protection within soil matrix [17]. Chemical protection involves formation of some recalcitrant compounds [18] like non- acid hydrolysable carbon fraction, aromatic compounds, double chained hydrocarbons and hydrophobic compounds which are not easily decomposed by microorganisms.

Change in soil carbon is a balance sheet of carbon input and output through mineralisation, loss, other emissions etc. [10]. So, the key for sequestering SOC is increasing carbon inputs and reducing carbon outputs. Cropping system biomass productivity has primary control over this carbon input through proper fertiliser, land, water management practices based on exiting soil and climatic condition. Integrated and balanced fertiliser application positively affect both above ground and below ground biomass and crop productivity. This adds more amount of organic matter to the soil directly in the form of straw returns, roots, exudates and organic manures directly. The organic carbon present in soil is very much prone to oxidation if neither biochemically protected (depends on its composition) not physically protected (in soil aggregates). So, researches focus on those practices

which are helpful to protect pre-existing soil aggregates and/or to promote the genesis of new soil aggregates or to achieve both objectives of CMP.

Important carbon management practices are:

1. conservation agriculture (CA),
2. Cover crop
3. Crop rotation and diversification
4. Integrated and balanced nutrition (use of organic amendments viz. Crop residue, FYM, Compost, Biochar)

4.1 Conservation Agriculture (CA)

This is the technology of a set of management practices which aims at conserving the natural resources and biodiversity in the crop land and are characterised by the three principles e.g., i) No/minimum soil disturbance, ii) permanent organic cover or cover crops, and iii) crop diversification. Each principle individually and combinedly contribute towards carbon enrichment in soil. Build-up of carbon in soil can be successful through increased input, reduced decomposition and loss or both. Cultivation of previously uncultivated land can lead to 20%–40% loss in the native carbon in the initial years following initial cultivation [19]. Restoring that carbon in soil through addition and protection can be a potential carbon management practice. Every input like fertiliser, pesticide and irrigation has a carry a 'hidden carbon cost, thus optimising their quantity in a crop management practice should be estimated in the carbon balance sheet [20]. Historically, excessive cultivation operations like tillage can expose SOC for decomposition by microbes which further may cause many land degradation problems such as erosion and soil structural decline. Enhanced soil disturbance triggers carbon losses from soil system via increased decomposition and erosion of SOM. All these ultimately adds to the atmosphere as CO₂ fluxes or to the water resource [21]. Soil carbon levels of agricultural soils are lower than corresponding soils under natural vegetation or fallow that indicates the potential for soil carbon storage. In agricultural systems, soil carbon levels tend to be variable and dependent on management practices. Reducing soil disturbance can reduce rate of oxidation of organic matter and provide protection to the microbial habitat. Rate of decomposition can also be reduced by introducing slowly decomposing residues in the rotation. Intensifying crop rotation, legumes and green manure crops in crop cycle, elimination of fallow period, cover crop and residue mulch enhances soil carbon input in the form of both above ground and below ground biomass. The principles of conservation agriculture rotate around the concept of biomass addition and its protection through less soil disturbance. Soil C level and its composition under no-tillage and stubble retention (SOC = 2.5%) was more than the same soil under 3 pass tillage and stubble burning (SOC = 1.5%) after 19 years [4]. Reduced tillage increases the potential of soil C sequestration over conventional tillage practices as described in **Figure 2**. The concept of achieving steady state carbon status in cultivated soil through maximisation of organic input (residues, root biomass, organic amendments) is depicted in **Figure 3**. Conservation agriculture technology can be a potential method for conserving soil moisture, supplying plant nutrient and mitigate pathogen, pest and weed infestation there by cutting off fertiliser, pesticide requirement. Every input like fertiliser, pesticide and irrigation has a carry a 'hidden carbon cost, thus optimising their quantity in a crop management practice should be estimated in the carbon balance sheet [23].

A study conducted by [20] Sapkota et al. (2015) in the Indo-Gangetic region showed that conventional rice- wheat cropping system has 27% higher GHG emission (in terms of CO₂ equivalence) as compared to zero tilled rice- wheat crop rotation with residue mulching [23]. Sapkota et al. (2014) found the carbon dioxide efflux so also the global warming potential of wheat (through life cycle analysis) for its unit production under conventional tillage based practice is 10 times higher than no tillage based production. Introduction of legume in crop rotation and residue addition to the soil help reducing fertiliser requirement and energy need in arable systems. Considering the fact that, the annual global fertiliser leads to an annual release of 300 Tg of CO₂ into the atmosphere during fertiliser manufacturing process [24], any management practice that will reduce the chemical fertiliser requirement with optimised output is highly environment friendly. They also explained that the release of every 2.6–3.7 kg CO₂ per every 1 Kg of synthesised N, is produced from fossil fuel thus causing a net contribution to atmospheric amount of CO₂ [24].

While the carbon sequestration in soil will occur at a certain point of time (until saturation) depending upon the soil type, reduction in emission owing to less energy requirement, fossil fuel consumption and machinery use will continue until the practice is carried out [25]. Zero tillage cuts the fuel consumption for land preparation so also CO₂ emission. (Erenstein and Laxmi 2008) [26] found that adoption of ZT in wheat- maize system of the IGP could save an average of 36 L diesel ha⁻¹ which is equivalent to a reduction in 93 kg CO₂ emission ha⁻¹ yr⁻¹ Sapkota et al. (2015) [20].

4.1.1 Mechanism of soil carbon sequestration in CA system

The carbon stock–enhancing effect of SOC management practice of conservation is possible due to reduced disturbance which is the prime factor in maintaining

Figure 2. Changes in SOC content in cultivated soil as a result of tillage pattern over years [4].

Figure 3.
 Mechanism of achieving steady state SOC through input addition. Adopted from [22].

soils physical stability. This physical wellness of a soil system has positive effect on microbial habitat, their activities and the natural ecosystem functions of soil like nutrient cycling, buffering capacity, cation exchange etc.

The first principle is no tillage which is growing crops in soil without causing soil disturbance except for sowing or reduced tillage that is significant reduction of soil disturbance through less frequent passes of tillage, tillage in specific portion of the field which is in form of strip or ridge and shallower depth of tillage. Second principle aims at keeping a permanent organic cover on the soil surface in the form of residue mulch, growing cover crops both of which addresses many aspects of soil protection in the form of hindrance towards water, wind erosion, improved soil aggregation, enrichment of substrate for microbial growth and functionality and many other chemical properties such as nitrogen fixation, carbon sequestration, etc. the third principle i.e. crop diversification is an essential tool for promoting better soil health as it has a role in allowing nutrient uptake of differently rooted crops from different depths, promoting microbial diversity, reducing disease and pest infestation there by allowing a better plant growth and biomass addition.

4.1.1.1 Aggregate formation and stabilisation

Soil particles are bound together by temporary (i.e., fungal hyphae and roots) and transient binding agents (i.e., microbial- and plant-derived polysaccharides through organic matter decomposition) [27]. In presence of these agents, aggregation is promoted and with time the microbially restructured carbohydrate molecules get attached with finer soil particles like clay and silt which is a stable form as compared to particulate organic matter (POM). With elimination of soil disturbance (tillage), soil organic matter gets strongly bound to clay particles in the form of macroaggregates and microaggregates within the macroaggregates. Again, microaggregates within the macroaggregates constitute a secure habitat soil microorganism, soil disturbance destroys the microbial habitat, affects its activity. In non-disturbed soil, the particulate organic matter present in macroaggregates get to be predominantly stabilised within microaggregates owing to the slow turnover rate [28]. On the other hand, a higher turnover of POM is seen due to tillage because they get exposed to rapid microbial attack preventing its incorporation into microaggregates as fine POM. In short, tillage leads to carbon loss through breakdown of C-rich macroaggregates and a decrease in microaggregate formation. Research has shown that 90% of total difference in SOC in soils of varying type and climate

is due to the microaggregate-associated C fraction [29]. Thus, a slower turnover of this fraction in zero tillage allows greater protection and stabilisation of coarse POM over time through mineral-bound C decomposition product formation in the microaggregates-within-macroaggregates promoting long-term soil C sequestration in agricultural soils. The process of aggregate formation and protection under no tillage system is shown in the right flowchart whereas, disruption due to tillage is described in the left (**Figure 4**), The bold lines are implicative of higher amount.

Figure 4. Aggregate formation in a no-tillage as well as conventional tillage system. Adopted from [30].

4.1.1.2 Microbial population and diversity

Not only microbial habitat, but also macrofauna population is promoted under no tillage practices in absence of physical abrasion and habitat destruction as happens under conventional tillage practices.

Availability of protected habitat and higher C- input directly influence microbial population in a positive way. Generally, in tillage induced environment there is dominance of *r* strategists (with high reproduction rates and fast colonisation capacities) in soil biota shifting the ratio towards higher mesofauna vs. macrofauna or bacteria vs. fungi [31] and thus increased mineralisation versus humification [32] as well as low stability aggregate formation [27]. A fungal dominated system is considered to be a better carbon trapper because of higher metabolic growth efficiency of such class, which assimilate much of substrate carbon in microbial biomass and by products but emit less CO₂. Higher the metabolic growth efficiency, lesser the loss of mineral associated carbon as CO₂ as the fungal products are more chemically resistant to decay [31]. The binding of microaggregates within macroaggregate by plant roots and microbial hyphae is described in **Figure 5**. The mechanism of higher microbial population (Fungi dominated) and aggregate stability are complementary to each other which is generally observed under high biomass input

conservation tillage system. A higher amount of microbially derived carbohydrate C, acid hydrolysable C, amino acids, amino sugars and glomalin content is observed under no tillage soil than a tilled one [33]. The complex interlinking of carbon substrate addition, improved soil physical structure and physical & biological activity enables higher carbon capture under a conservation agriculture management system. More number of binding agents in an undisturbed agricultural soil

Figure 5.
Mechanism operated in soils under CA practice for enhancing C-pool size.

Figure 6.
Macro and micro aggregate formation in soil through binding agents. Adopted from [35].

Location	Cropping system	Depth	Years of adoption	SOC change Mg ha/yr	Reference
China	Maize, wheat, rice, soybean	0.2–1.0	Avg: 6.5	+0.25	[36]
Indo-Gangetic Plain	Rice- Wheat	0.05–1.05	2–26	+0.14	[34]

Table 4.
Impact of conservation agriculture on SOC in different countries of Asia.

promotes water stable aggregate formation and carbon sequestration within the structures. A higher enzymatic activity is also observed under CA.

The main social issue with farmers of IGP are, less time interval between harvesting of kharif crop and sowing of succeeding crop, fodder requirement of domestic animals, use of crop residue as a source of energy for domestic purpose. Mostly farmers adopt the simple way of residue management i.e., residue burning which is undoubtedly a huge source of CO₂. In that case, may the carbon addition be very small due to residue return to the field that would otherwise have been emitted to the atmosphere, is a sure shot CO₂ efflux mitigation principle (Powlson et al., 2016) [34] (**Figure 6, Table 4**).

4.2 Cover crop

The intercrops or catch crops can be grown in field instead of keeping the land fallow before sowing of the next fallow crop. A *cover crop* is a *crop* of a specific plant that is grown primarily for the benefit of the soil rather than the *crop* yield. Legumes such as vetch, clover, cowpea; green manure crops, a mixture of grasses like ryegrass, oats, winter rye etc. can be chosen as cover crops. In soils health prospect the benefits of cover crops are many starting from erosion control to nutrient trapping. In crops point of view they are excellent for reducing weed and pest infestation in the crop land resulting in a better crop stand. As a direct source of organic biomass to the land, growing cover crops is one of the most effective carbon management practices in Asia. The process of carbon management through cover crop is another interlinked phenomenon of soil erosion control by creating hindrance for the rain drops to splash on the ground directly, soil structural improvement and protection, microbial activity accelerator through supply of substrate for their growth and carbon sequestration [37]. Legumes as cover crops enrich the soil with nitrogen whereas cereals and brassica are excellent nutrient scavengers (scavenge nitrogen from losses). A large part of the cover crop is added to the soil in the form of root biomass which was found to be a relatively stable carbon pool than the above ground residue [38]. No tillage legume can act as a potential sink of GHG with global warming potential of –971 to –2818 kg CO₂ equivalent ha⁻¹ year⁻¹ as observed by Bayer et al. (2016) [39] in sub-tropical ultisols of Brazil. He also suggested that, these systems may act as a potential source of N₂O emission but the net effect is fully offset by CO₂ retention in soil organic matter which accounts for –2063 to –3940 kg CO₂ ha⁻¹ year⁻¹. Along with below ground biomass, the cover crop is anyway an additional source of carbon enrichment to the soil as compared to a fallow period. A meta- analysis conducted by Poeplau and Don (2015) [40] concluded cover crop to be higher estimate management practice than sewage sludge application with an accumulation rate of 0.32 ± 0.08 Mg C ha⁻¹ yr.⁻¹ until saturation is reached in a soil depth of 22 cm (mean) in 30 sites worldwide (in Asia sites under study are from India and Japan). This cumulative carbon sequestration through cover cropping has the potential to compensate for 8% of the annual

direct greenhouse gas emissions from agriculture [41]. Dynamics of nitrogen is very essential for carbon stabilisation in soil. C: N ratio, quality of nitrogen is a major factor controlling nitrogen dynamics in soil. a low C:N ratio plant like legume, early killing of cereal crop can release nitrogen faster into the following crop whereas high C:N ratio cereal grains slow down N release rate. Nitrogen is very much needed in balancing soil organic carbon. Thus, reduced tillage system and high C:N ratio residue can temporarily increase optimum N requirement in crop field that will add to long term carbon storage in soils. Cover crops can contribute this N either by scavenging residual N or by N₂ fixation by legumes.

4.3 Crop diversification or rotation

Monoculture is a technique that favour strong outbreak of diseases and pests. Again, due to same root architecture in every season, plants access nutrient from a specific depth. These affect plant growth and production. On the other hand, the stratified root architecture associated with crop diversification allows plants to uptake nutrients from various depths of the soil. Rhizosphere provides suitable environment for microbial diversity and proliferation in different level of the soil. Crop diversification has been shown to reduce the emergence and damage of such pests and diseases. This promotes better above ground as well as below ground biomass production in crop plant by which crop diversification directly contributes to carbon enrichment in soil. Crop rotation or mixed cultivar use instead of single genotype are found to improve resilience towards climate change extremities, pest, disease occurrence, enhance yield stability and reduce fertiliser footprint which ultimately cuts contribution of crop production towards CO₂ emission. A study conducted by Hu et al. (2016) [42] showed that there is 46% less soil respiration and 10% less emission in wheat- maize intercropping as compared to maize monoculture in north-west China. In case of intensive cropping systems, minimum one legume crop is necessary for soil carbon stabilisation along with other soil quality benefits. Legume plants are characterised by deeper root system, high leaf shedding, higher root exudates accelerate rhizospheric activity [43]. The quality and quantity of both root exudates and microbial polysaccharides (rich in lignopolyphenol complexes) promote macro and meso aggregate associated carbon storage in “rotation with legume” system than “cereal- cereal” system which is a good indicator of carbon sequestration [44, 45]. A life cycle-assessment (LCA) review conducted by Clune et al. (2017) [46] from 2000 to 2015 around the world highlighted that pulses have a very low Global Warming Potential (GWP) values (0.50–0.51 kg CO₂ eq kg⁻¹ which makes inclusion of a pulse crop in crop rotation, a win-win situation.

Pulse cultivation has other beneficial effect on soil environment viz.; pulses during summer can conserve moisture because soil covering through litterfall protects soil surface from atmospheric temperature. Not only the exudate or biomass quality but the management practices associated with crop rotation (irrigation, fertiliser dose, nitrogen fixation, amount of residue recycled for different crop rotations) cause variation on biomass input into a system. Legume crops acquire their N from biological nitrogen fixation (except for starter dose of nitrogen fertiliser) rather than from the soil as nitrate a slight decrease in pH of soil occurs. The reduction in soil pH in neutral and alkaline soil environments promote microbial activity in root zone and increase the nutrient availability [45]. Therefore, pulse in rotation enhances the macroaggregates rather than cereal- cereal system. Though the results of legume in rotation are strong for higher carbon management, a cereal- cereal rotation improve the passive carbon pool because higher carbon: nitrogen ratio of such crop residues [45]. Cereal in a rotation has also found to be important in environmental aspect as per a study conducted by Senbayram et al. (2016) [47] who found that monocropped faba beans lead to three times higher cumulative N₂O emissions than that of

unfertilized wheat whereas faba bean wheat intercropping could lower the cumulative N₂O emissions by 31% as compared to N-fertilised wheat.

Proliferated root condition under diversified cropping system supports a hierarchy of aggregate formation (macroaggregates followed by microaggregates within macroaggregates). Plant roots and residues bind the individual soil particles together to form macroaggregates then fine root hairs grow into these aggregates. The organic acids, enzymes, and other C-rich compounds exuded by these roots support higher microbial populations and act as the nucleation centre for microaggregate formation [48, 49]. The microbially altered organic compounds get polymerised and are then strongly bound to finer particles (silt & clay) inside of the macroaggregates. These newly formed occluded microaggregates are C and N enriched [48, 49].

4.4 Integrated and balanced nutrient management

With increase in demand of food per capita per unit land area, farmers are adopting higher fertiliser application in hope of getting higher yield. But in contrast the expectation, over use of chemical fertiliser result in severe soil degradation which is a major contributor towards soil carbon loss and higher GHG emission. As a correction measure to such issue, many scientists have looked for the role of integrated (chemical+ organic) and balanced fertilisation on GHG emission reduction and soil carbon enrichment. As per a study conducted in subtropical north-western states of India, application of organics along with chemical fertilisers reduces the gaseous N losses as compared to fertiliser nitrogen alone in rice-wheat system [50]. Addition of organics no doubt acted as the primary source of denitrification, but the carbon balance was still positive. The higher yielding cropping systems created a scenario of higher CO₂-C consumed by crops for photosynthesis than the total flux of CO₂-C from rice-wheat system even with the use of organics thus making it a sink of atmospheric CO₂-C [50].

Integrated nutrient management (INM) technology improves the physical, chemical and biological activity of the soil, which leads to a healthy plant population and higher yield. Organic treatments like FYM, sulphitation press mud (SPM), green gram residue (GR) and rice-wheat crop residues (CR) may consistently increase biomass yields and increase C inputs in soil. The strong influence from increasing C stock through long-term balanced fertilisation under rice-wheat cropping system was found by Nayak *et al.*, 2012 [51]. Organic material incorporation improved soil aggregation and structural stability and resulted in higher C content in macroaggregates, thereby improved C sequestration potential in soils. However, the C accumulation in aggregates may determine by the kind and source of organic inputs. Thus, study by Das *et al.* (2014) [52] found that a combination of GR in rice and FYM in wheat significantly improved C content in macroaggregates, 100% N application through inorganic fertiliser. However, CR incorporation enhances coarse particulate organic matter (>0.25 mm) which substantially increase C content within macroaggregates. Intensive rice-wheat system through combination of inorganic and organic fertilisers and crop residues increases C content in microaggregates- within-macroaggregates [53] indicating higher potential of C stabilisation in soil.

Organic amendment like FYM, vermicompost, biochar etc. have higher humification rate constant but less decomposition rate thus, improve the amount and stability of SOC through their addition. An incubation study by Naher *et al.*, 2020 [54] described that carbon mineralisation rate was 0.011 tonne year⁻¹ for INM followed by balanced fertiliser and control which in turn enhance the scope for SOC sequestration in soil for sustainable rice production.

Treatments	Carbon efficiency ratio	Global warming potential (kg CO ₂ ha ⁻¹)	% increase in yield over control	% increase in emission over control
NPK	13.82 ± 0.82	540.60 ± 21.25	—	—
NPK + Green manure	9.94 ± 0.24	887.40 ± 12.11	10.70	64.15
NPK+ Azolla compost	16.90 ± 0.25	625.20 ± 13.03	27.43	15.66
LSD (T)	0.634	21.068		

Table 5.
Effect of INM on emission and yield.

Soil attributes	Soil functions
Soil physical properties	Organic amendments support aggregate formation, aeration, higher water holding capacity
Nutrition supply	Release of nutrient over a long period of time, improved use efficiency, higher SOC, more aggregate SOC, reduce phosphate fixation, reduced the mining of K from the soil
Soil reactions	Increase CEC, buffering, rhizospheric elemental transformation
Soil biological property	Microbial species diversity, soil enzymes, microbial biomass C (MBC), slow establishment and persistence of pathogens
Agronomic properties	Better root establishment, higher grain, straw production

Table 6.
Effect of INM on various soil properties for better soil health and crop production.

A study conducted by Bharali et al. (2018) [55] in the north-eastern India showed that addition of organics (Azolla compost or green manure) along with chemical fertilisers resulted in higher emission worth of higher global warming potential however, the carbon efficiency ratio and amount of fixed carbon in terms of grain yield was found to be higher and lower in case of Azolla compost as compared to chemical fertiliser alone. Likewise, in case of NPK + green manure, there is 64% higher emission over the control, a lower carbon efficiency ratio but higher total C fixed in a form of grain carbon (Table 5). Though INM is not a direct solution for reducing C efflux, the extra organics added may result in more emission as compared to sole chemical fertiliser addition, it also contributes to sufficiently higher C fixation in the form of grain C which ultimately shows to have a positive carbon balance due to INM.

A review done by Wu and Ma (2015) [56] shows the effect on INM on different soil properties and crop growth in countries of Asia is summarised in Table 6.

A meta-analysis conducted by Waqas et al. (2020) [57] all over China to study the effect of balanced, imbalanced, integrated, sole fertilisation and their combinations on yield sustainability (YSI), yield variability index (YVI) suggest that balanced and integrated fertilisation has highest YSI and lowest YVI and balanced chemical fertilisation has less YVI as compared to sole organics addition or imbalanced chemical fertilisation. The result supports the fact that integrated and balanced fertilisation supports carbon addition through higher above ground and below ground biomass production. Even imbalanced+ organic fertilisation and organic fertilisation alone can increase SOC due to direct addition of stabilised carbon through organic amendments. Organic amendments are also supply additional nutrients (N, P, S, etc.) into the soil which are responsible for production of fine

fraction of soil organic matter [58]. The direct and indirect carbon input through integrated fertiliser management is a great adoptive measure as carbon management practice. In general, cold temperature promotes carbon sequestration due to low rate of organic matter decomposition but in higher temperature region with higher productivity and consequently increased biomass carbon input into soil [59], SOC can be improved through stable aggregate formation.

Sole and continuous use of chemical fertilisers inhibit the micro-organisms and their biochemical compositions, which reduced the aggregate formation. But the fresh organic matter added through organic amendments supply promote microbial polysaccharide formation (water soluble and hydrolysable substrate) that also promote aggregate formation. In completely no fertiliser condition, higher root extraction causes shattering of macroaggregates and breaking up soil structure [60].

Biochar as an organic amendment is also a great choice because the carbon-rich material has many organic functional groups to which act as bridge to form strong complexes with soil and is also helpful to increase soil aggregation through charged surface, porous structure and high cation exchange capacity [61].

Biochar amendments has two mechanisms of improving SOC dynamics (1) promoting soil aggregation thereby physical protection of bound SOC (2) Negative priming by means of higher recalcitrant organic substrate pool having low decomposition rate [62] (**Tables 7 and 8**).

Treatment	Carbon mineralisation rate (t yr ⁻¹)	Carbon stock (t ha ⁻¹ year ⁻¹)	Carbon sequestration (kg ha ⁻¹ year ⁻¹)
Fertiliser control	0.009	10.95	-213
Balanced fertiliser	0.010	17.30	-72.15
INM	0.011	26.30	127.86

Table 7.
Carbon sequestration in soil with rice–rice–fallow cropping sequence for 10 years [54].

Country	Control	NPK	INM	Reference
New Delhi, India	7.53	8.50	11.08	[63]
Kanpur, India	3.73	4.59	5.45 (50% RDF+ FYM+ residue+ biofertilisers)	[45]
Bangladesh	9.8	13.3	17.1 (RDF + Gr. manure)	[64]
China	13.81	13.40 (Only N)	15.12 (RDF + Straw/Biochar) 15.22 (RDF + Biochar)	[65]

Bold letters are to make the values distinctly visible from treatment details only.

Table 8.
Total organic carbon (TOC) content under INM and chemical fertilisation practice in various regions of Asia (TOC given in g/kg).

5. Conclusion

In the degraded land Soil organic carbon acts as the centre of soil health through positive regulation of soil physical, chemical, biological and ecological functions. The integrated management practice like conservation agriculture does not only

add carbon to the soil directly but also reduce fossil fuel CO₂ emission, oxidation of SOC. Cover crops and crop diversity are beneficial for combating disease- pest occurrence, support healthy above ground and below ground biomass production. Legume in a crop rotation supports aggregate formation and stabilisation and ultimately protects the aggregate associated carbon through chemical polymerisation and physical occlusion. INM is beneficial over imbalanced chemical or sole chemical fertiliser application. Though biochar is another effective amendment for carbon sequestration in agricultural land, the higher carbon foot print associated with its production technique (CO₂ production during pyrolysis and more CO₂ emission from amended plots) can offset it as a climate change mitigative- adoptive practice. Soil C sequestration is not a permanent solution for all climate change related issues but is a holistic approach to restore degraded soil, reduce erosion, increase agroeconomic yields and reduce CO₂ emission into the atmosphere at the same time. Thus, careful selection of carbon management practice according to climatic and soil condition is necessary for making it agriculturally and environment friendly.

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