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Soil Carbon Sequestration for Sustainable Soil Health and Agricultural Productivity in India

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ABSTRACT

Soil carbon sequestration has become a key approach to enhance the soil health and agricultural productivity and to enhance the climate resilience in Indian farming systems. Widespread degradation of soil organic carbon (SOC) in the agro-ecological regions of India has affected soil structure, nutrient availability, water retention and biological activity, thereby affecting performance of crop and increasing the vulnerability to climate variability. This review summarizes recent information on soil carbon status and dynamics in Indian agriculture and critically analyzes the mechanisms affecting the soil health and production by SOC. Long-term field experimental and regional studies have shown that conservation agriculture, integrated nutrient management, organic amendments, crop residue retention, agro forestry, and novel carbon enhancing technologies are markedly able to increase the SOC stocks, stabilize and in many cases, enhance crop yields. The review also cites significant limitations to large-scale adoption such as measurement and monitoring issues, regional differences in sequestration potential, socioeconomic trade-offs, and smallholder barriers to adoption. Some of the major research priorities are identified to follow-up the successful scaling such as the establishment of low-cost monitoring structures, regionally specific managerial plans, and enhanced extension and policy integration. It is therefore critical to strengthen soil carbon stocks in order to attain sustainable soil health, resilient agricultural production as well as long term food security in India.

1. INTRODUCTION

Carbon sequestration in the soil has become one of the pillars of sustainable agriculture due to its location at the nexus of soil wellbeing, agricultural output, and the reduction of climate change (Mounika et al., 2025). Soil organic carbon (SOC) is not just an indicator of soil quality; it forms the basis of the soil structure, aggregation, water retention, nutrient recycling, and biological processes - processes that together define the efficiency of crop utilization of rainfall, irrigation and fertilizers. In India, where agriculture provides a significant source of livelihood to a high proportion of the rural population and where the variability of climatic conditions is accelerating, enhancing SOC is becoming a viable means to enhance productivity and resilience as well as undo the national objectives of climate and land restoration (Taylor et al., 2021).

Large-scale soil assessment signals are indicative of an urgency. Analyses based on the Soil Health Card (SHC) ecosystem show that a large proportion of the samples tested have low organic carbon status. Indicatively, the Centre for Science and Environment (CSE), based on SHC-associated data,

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stated 48.5% of the assessed soil samples were low in the content of organic carbon-a location on erosion that has direct assessment on crop responsiveness to inputs and soil susceptibility to erosion and stresses of drought. Such evidence is consistent with the long standing agronomic knowledge that many Indian cultivated soils have suffered SOC depletion because of continuous cultivation, reduced organic matter return, residue removal/burning, imbalanced fertilization, and erosion especially in intensively farmed areas. Operationally defined in relation to soil testing and advisory, low SOC is often defined in terms of threshold categories. The majority of Indian soil-testing systems define SOC of less than approximately 0.5% as low with higher bands describing a medium to high position. Although thresholds depend on the type of the soil and on agroecology, they are helpful to monitor the conditions of soil conditions at a larger scale, as well as to prioritize the interventions. Notably, it is not only the quantity of carbon in soil that is being discussed in the SOC story, but what the form of carbon is, i.e. labile or stable fractions, particulate or mineral-association carbon because these pools affect agronomic benefits and also the longevity of sequestration (Jat et al., 2023).

India's agricultural landscapes are exceptionally diverse (encompassing arid, semi-arid, sub-humid, humid, coastal and mountain ecology) and consequently the SOC dynamics and sequestration potential are very diverse. An effective prescription cannot be uniform. For example, Indo-Gangetic Plains, rainfed Deccan systems, coastal deltas and tribal hill agroecosystem differ in terms of texture, mineralogy, rainfall regime, cropping intensity, availability of biomass. This diversity ensures India is a very suitable context for a review linking SOC sequestration and soil health consequences to agricultural productivity, as well as finding realistic "pathways" that are appropriate to different regions and types of farms. The policy discussion on the world scene has placed an increased focus on SOC as a natural solution to climate change. The 4 per 1000 program, introduced into the climate policy sector, popularised the aspirational goal of raising global stocks of soil organic matter by 0.4 percent/year, and brought into the limelight soils as a vital carbon sink as well as their contribution to food-security. Nonetheless, studies also warn that it is vital on climate, saturation of soil, biomass availability and management, so country and region specific analysis is vital. Simultaneously, the IPCC has also given methodological advice to assessing changes in carbon stocks in soils under cropland management, which has been the focus of the centrality of soils in land-sector greenhouse gas accounting. More recently, IPCC evaluations also highlight that carbon management of soils in croplands and grazing lands is also one of the largest mitigation opportunities, which is sensitive to incentives and conditions of implementation (McGlynn et al., 2022).

The advantages of SOC sequestration are most powerful within the context of India, where sustainable soil health and productivity are the most important variables compared to carbon (Vardhan et al., 2025). SOC enhances aggregation and infiltration, lessens crusting, increases plant-available water, promotes microbial diversity, and adds to nutrient buffering-all of which may make yield less unpredictable during heat waves, dry periods, and unpredictable precipitation. The soils of SOC-rich tend to be more efficient with respect to their fertilizer-use, and farmers are able to get better returns with the same unit input. To systems dominated by smallholders, such gains are important since they will translate to less risk and more stable production. Although this promise is given, the trade-offs and difficulties of measurement limit the pathway to building SOC. The main competing sources with livestock feed and household needs are crop remnants; biomass and labor limit the use of composting and manuring; the use of conservation agriculture may be constrained by machinery accessibility and weed control; the SOC increments may be low in certain systems, which means that the application of such practices requires long-term persistence. Furthermore, soil carbon monitoring, reporting and verification (MRV) is still complicated based on the spatial variability and high cost of sampling despite the international development of MRV frameworks (Searchinger et al., 2019).

Against this background, the present review is a synthesis of evidence on soil carbon sequestration in the Indian agriculture with a special focus on how SOC rebuilding can strengthen soil health and improve agricultural productivity. The review highlights (i) the processes linking SOC to soil functionality, (ii) the prevailing situation and trends of agroecological settings in India, (iii) management practices that are proven and (iv) the research gaps and priorities to scale the SOC-enhancing practices in a scientifically plausible and socioeconomically viable manner (Bhartiya et al., 2024).

2. CONCEPT AND MECHANISMS OF SOIL CARBON SEQUESTRATION

Soil carbon sequestration is the process when atmospheric carbon dioxide (CO2) is transferred into the soil carbon pool and stored for different periods of time, which reduces the concentration of greenhouse gases in the atmosphere. This process takes place in Agricultural landscapes through the interaction between plants, soil organisms, soil physical and chemical environment and forms the basis of climate mitigation as well as soil fertility enhancement. At the most basic level, carbon enters the soil system via the photo-synthesis of plants. Through photosynthesis, plants absorb CO2 in the atmosphere and convert it into organic matters including carbohydrates, lignin and proteins, which are later released into soil by root exudates and crop litter and biomass present at the field of harvesting. These inputs are then converted by soil microorganisms in the process of decomposition, assimilation, and stabilization to decide the amount of carbon that is stored in soil and in what form (Nair et al., 2015)

2.1. Soil Carbon Pools and Forms

The organic carbon (SOC) of soils includes a variety of carbon-bearing substances which vary in terms of biochemical composition and recalcitrance. These consist of labile fractions, like simple sugars and microbial biomass, which turn-over on a short-term basis, and more resistant fractions, including humic materials and mineral-associated organic carbon, which lasts decades or centuries. This is because the abiotic and biotic processes that affect the development of stable SOC involve aggregation in the microstructures of soil and the establishment of chemical relationships between soil minerals. The examples of humic substances include complex organic compounds composed of condensation and conversion of plant and microbial residues, and they are generally connected with enhanced soil structure and extended carbon storage (TIWARI et al., 2022).

2.2. Stabilization Mechanisms

The amount of carbon that is sequestered in soil is not only dictated by the amount of input, it is also dictated by the efficiency with which organic carbon is stabilized to resist microbial degradation and physical breakdown. The SOC stabilization is caused by several important mechanisms:

- Physical Protection: It is also possible to preserve organic carbon in soil aggregates, and especially in microaggregates, where mechanical barriers restrict the accessibility of microorganisms and enzymes. Mineral-organic complexes also help in stability, by blocking the organic molecules into structures that are resistant to decomposition.

- Chemical Protection: SOC is able to sorb onto and chemical bond to clay minerals and metal oxides and this creates long-lasting associations that inhibit faster decay. Soils that are fine-textured having more content of clay usually have more carbon due to the improved binding capacity.

- Biological Processes: The microbes in the soil are active in dynamics of SOC in a twofold way. Although the CO2 is released into the atmosphere during the decomposition process, microbial biomass and the produced biochemical compounds exhibit the potential to increase the carbon sequestration rates, by adding to the development of an immobile organic matter and facilitating aggregation. Microbial communities in soils, therefore, define the mechanisms and periods of SOC persistence (Lehmann et al., 2020).

2.3. Soil Carbon sequestration Controls

The possibility of soil carbon sequestration is different in a broad sense in relation to landscapes, as well as, contexts of management. Some of the key controls are:

- Soil Texture and Mineralogy: Clay soils are generally larger in carbon storage than the sandy soils since they provide more surface area to bind the organic material and more physical protection of the carbon contained in the aggregates. Loamy soils tend to exhibit moderate capacities in soil sequestration through equilibrium of growth of roots, activity of microbes and aggregate development.

- Climate and Environment: Both temperature and humidity have a great impact on microbial decomposition and the growth of plants hence, on SOC input and loss. Moisture in the soil controls the actions of the microbes and breakdown of organic matter under optimum soil moisture conditions, resulting in carbon storage and extremes (drought or waterlogging) leading to the disruption of sequestration.

- Land Use and Management: Tillage, reside management, crop rotation, organic amendment application and conservation agriculture are considered to have a major impact on the SOC dynamics, through changes in the carbon inputs and stabilization processes. Soc levels may be increased through conservation tillage, cover cropping and application of bio-organic amendments compared to more conventional intensively tilled systems (Bhartiya et al., 2024).

2.4. Integration of Agricultural Systems

The physiological process of soil carbon sequestration in agriculture needs to be interpreted concerning the productivity and the health of the soil. By enhancing SOC, soil structure is improved, and water is better retained as well as nutrient cycling which can result in a better crop performance and resilience to climate stress. However, the rates of carbon accumulation and the longevity of the newly sequestered carbon require continued management to promote carbon input and minimize loss, as well as the inherent soil and climatic conditions. Thus, the combinations of SOC improvement with agronomic productivity, including plant breeding, using crop residues, maximizing organic additives, and using conservation agriculture are the focus of attaining ecological and economic advantages (Peddi et al., 2025).

3. SOIL CARBON STATUS AND TRENDS IN INDIAN AGRICULTURE

3.1. Carbon Distribution of the soils in the Indian Agro-Ecological Regions

India's soils have a wide variability in their SOC level, which is due to the variations in climate, vegetation, cropping systems, and soil type. In the past, the soil organic carbon content of the Indian agricultural soils was higher, with the average levels of soil organic carbon being close to and even above about 1 per cent of soil organic carbon in the 1950s and previous decades. However, more recent assessments suggest that there has been a strong downturn in this regard with many cultivated soils now showing SOC contents in the order of 0.3 - 0.4 per cent or less in major production regions. This is a reduction of long-term continuous cropping with insufficient return of organic matter, removal of plant residues and other management pressures. The soils with forests and natural vegetation are likely to have a greater carbon stock than the cropped lands and forest soils in India are estimated to have significant storage of carbon in the top meter of the soil. An example is that the soils of Indian forests were estimated to contain 4.1 petagrams (Pg) C in the top 50 cm of soil and 6.8 Pg C in the top 100 cm of soil depth as an example of the higher sequestration capacity in less-disturbed ecosystems compared with intensively farmed croplands (Rajan et al., 2021).

3.2. Effect of Land Use Change and Crop System on SOC

Decades of agricultural activities such as conversion of land to intensive agriculture, marking (to remove residues which can be used as fodder or burnt), and organic amendments have played a role in SOC depletion. Estimates based on surveys conducted for the nutrient content of soils under the national Soil Health Card (SHC) scheme show that around 48.5 per cent of all soil samples tested are low in organic carbon, indicating widespread depletion of the country's soils. Cropping systems also differ in SOC levels. Monocultures which have been formed over long periods, particularly with high residue extraction and intensive tillage (as in some areas of the rice-wheat system) are associated with less SOC stocks than systems with rotated rotations, legumes, and perennial elements. Rainfed and dry land systems tend to have lower SOC in terms of reduced biomass returns and increased erosion and those with high biomass productivity and retention tend to have relatively good SOC status. These variations represent climatic effects as well as management histories (Siddique et al., 2023).

3.3. Major Drivers of Soil Carbon Depletion in India

Many factors have contributed to SOC decline over the past decades. Intensive cultivation under the Green Revolution model greatly increased cropping intensity and yield per unit area but often at the cost of soil organic matter, as the crop residues were removed, burnt or otherwise not returned to the soil. Continuous tillage increases the rate of oxidation of organic matter, which releases SOC to the atmosphere and decreases stable reserves. Unbalanced use of fertilizers and actual insufficiency in the substitution of organic inputs further deplete soil making the stocks of carbon and the overall soil fertility weak. These trends are in line with the concerns that have been expressed by soil researchers and agricultural scientists throughout national reviews and soil assessments (Wani et al., 2018).

3.4. Present Estimates of Sequestration Potential of Indian Soils

Indian soils have still the potential to increase their carbon sequestration, though most of them have been depleted, due to change of management practices to improve organic matter inputs and stabilization of soils. The previous estimates of soil carbon sequestration capability in India indicated that annual sequestration rates of several teragrams (Tg) of carbon per year, with certain ranges being estimated in restoration of degraded soils, erosion control and implementation of suggested soil management measures were possible. As an example, indicative values encompass possible SOC increases of 6 - 7 Tg C/yr due to the better management of agricultural systems alone though the actual rates which are achieved are all a matter of climate and cropping systems and biomass availability.

The field of soil carbon also suggests that in future there are prospects of studying deeper layers of SOC beyond the traditional 0-30 cm layer, with the emerging research using machine-learning and predictive mapping to gain a more accurate understanding of deep SOC pools of multiple meters under diverse land uses. Such approaches improve the knowledge of carbon storage potential of Indian agricultural soils and can contribute towards more sophisticated SOC bookkeeping and management approaches (Reddy et al., 2020).

4. ROLE OF SOIL CARBON IN SOIL HEALTH IMPROVEMENT

Soil organic carbon (SOC) is one of the key determinants of soil health since it affects soil physical, chemical and biological properties, which collectively determine soil capacity to support plant growth, and hence agricultural productivity. Soc is well known in agronomical and ecological studies as an important part of soil organic matter and as holistic soil health indicator, sensitive to management and environmental circumstances.

4.1. Soil Structure and Physical Properties

SOC is critical towards the enhancement of physical status of the soil. Organic carbon is a binding substance which contributes to the formation of stable aggregates of soil particles, increasing the soil structure, porosity and erosion resistance. Aggregation of soil enhances water penetration and retention, decreases mass density, and decreases prone to crusting and compaction, all of which are essential in much of the rainfed-based and monsoon reliant Indian agriculture.

Enhanced structure also gives better penetration and movement of roots to enable the crops to access water and nutrients better, particularly in climatic stress like drought. A higher SOC content can mean improvements in available water capacity, substantially, which would improve the resilience of crops during dry spells, and stabilise yields from crop to crop.

4.2. Chemical Properties and Nutrient Cycling

SOC plays an important role in the chemical fertility of soil. As a component of soil organic matter, carbon improves cation exchange capacity (CEC), which improves the ability of the soil to hold essential nutrients - like potassium, calcium and magnesium. The increased CEC is especially significant in rough-textured soils, as the retention of nutrients based on minerals might be low. In addition, SOC is a storehouse of essential elements like nitrogen, phosphorus and sulfur. Organic carbon promotes nutrient cycling through the breakdown and mineralization of organic matter and transforms organic matter into accessible plant nutrients. These biological processes of turnover enhance the efficiency of nutrients and decrease the reliance on external source of fertilisers with time.

4.3. Biological Activity and Microbial Dynamics

SOC is the base of energy and substrate for the existence of microbial communities in the soil. Several and dynamic communities of bacteria, fungi, earthworms, and other soil fauna depend on organic carbon to grow and reproduce. This is a biological action principle in the active decomposition of organic matter, turnover of nutrients, and prevention of soil-borne pathogens. Increased microbial biomass and activity has a positive relationship with the soil fertility and resilience. An example is that SOC-rich soils tend to be more active in the respiration and enzyme activity of microbes, increasing the productivity and efficiency of decomposition process and soil. More so, the dynamic relationship between soil biota and organic carbon leads to the development of stable humus and aggregate structures which enhance physical and chemical soil enhancements (Paul, 2016).

4.4. Soil health and Crop Performance implications

A combination of improvements in physical structure, chemical fertility, and biological activity results in SOC being a whole soil health indicator. Soils that are rich in organic carbon have better nutrient and water utilization efficiency that in most instances reflects into stable and steady crop development. Farmers have often noted that soils with high carbon content are more stable in yield particularly when they are under stress like during intermittent drought or unpredictable precipitation, a common farming problem in most parts of India.

In Indian context where soil health issues are correlated to large-scale lack of organic carbon (as reflected in the Soil Health Card data at national level) SOC augmentation has ecological and productivity benefits. Indicatively, low proportions of organic carbon in soils in agriculture limit nutrient fixation and microbial activity, which worsens soil degradation and compromises the harvest. This pattern can be reversed by improving the management practices of the land like retention of residues, adding organic amendments, and minimizing the use of tillage that may enhance the performance of the soil (Mishra et al., 2023).

5. SOIL CARBON SEQUESTRATION AND AGRICULTURAL PRODUCTIVITY

Soil carbon sequestration has a direct contribution to agricultural productivity through enhanced efficiency in which the soil supplies water, nutrients, and physical support to crops. Productivity improvement of increased soil organic carbon (SOC) is based on the complexity of interrelated functions of soil that improves crop growth, stabilizes harvests, and means becoming less susceptible to climate stress (Pradhan et al., 2024; Vardhan et al., 2025). Various long term agronomic studies in various agro-ecosystems have shown that soils with elevated SOC are always more responsive in yield and stable in production than the carbon-depleted soils (Ghimirey et al., 2025).

5.1. Relationship between Soil Carbon and Crop Yields

SOC affects the yield of crops by its impact on soil structure, nutrient availability and biological activity. The increase in the level of SOC leads to enhanced soil aggregation and porosity which enhance root growth and aeration. This allows the crops to have greater access to water and nutrients within the soil, especially under less than optimum moisture conditions that commonly exist in Indian rainfed systems. Research work on cereal based systems of crops has demonstrated that even minor increases in the SOC over that of the soil can profoundly increase the potential of a crop by promoting the growth and efficiency of roots and nutrient uptake. In Indian condition, long term experiments under Rice wheat systems, maize based systems, and rainfed cropping have repeatedly reported higher yield under organic amendments and residue retention to build SOC than the conventional nutrient management using mineral fertilizer only. The increase in yield is frequently credited to the increase in the soil structure and augmented availability of nitrogen and phosphorus due to the augmentation of the organic matter turnover (Meena et al., 2023).

5.2. Impact on Water and Efficiency of Nutrient Use

One of the most significant productivity benefits of SOC is that it can help improve water use efficiency. Organic carbon increases the water holding capacity of the soil through improving aggregation and increasing the percentage of stable pores. This enables soils to retain more of the rainfall and irrigation water and to release it slowly to crops. Higher SOC can also be used in monsoon-reliant areas in India, where it causes crop water stress to be lower in times of dry spells, resulting in more predictable yields during unpredictable rainy years. The efficacy of nutrient use by SOC also increases. Organic matter serves as a reservoir of key nutrients and helps to improve the cation exchange capacity of the soil to reduce leaching of nutrients and thereby improve fertilizer recovery by the crop. With the decomposition of organic matter, nutrients are made available in tandem with crop requirement, enhancing nitrogen and phosphorus supply and decreasing the reliance on the high fertilizer input. Combined nutrient management systems involving organic and inorganic sources of nutrients are thus generally accepted as a viable solution to a sustainable route of ensuring the sustainability of soil as well as crop productivity.

5.3. Stability of Yield and Resilience to Climate

In addition to absolute yield growth, SOC has a vital function in yield stability an especially significant outcome in the face of unstable climate conditions, which are becoming a challenge to the smallholder farmers. Crops grown on soils with high organic carbon levels prevent heat stress, drought and temporary flooding due to the ability to stabilize soil temperature, increase infiltration and sustain soil moisture when subjected to stress. This buffering capacity has the effect of diminishing year to year yield variations and minimizing the risk of crop failure which is the core of livelihood security in the smallholder agribusiness systems of India. Biological resilience is also promoted by greater SOC through maintenance of the diverse soil microbial habitat that aids in the reduction of diseases and biocycling of nutrients. These biological interactions enhance the health of crops and vulnerability to pests and diseases, which increases productivity and system stability further.

5.4. Long Term Implications for Productivity of Indian Farming Systems

The productivity benefits of SOC accumulation are greatest on a long-term basis. Although the immediate reactions of yields in the short run might be average over the first several years of implementation of carbon-building activities, a long-term management will result in long-term enhancement of the soil functioning and productivity. Field experiments conducted over a period of time in India have demonstrated that SOC stocks can be restored by continuous application of organic inputs, retention of residue, diversified cropping, and reduced tillage, leading to an increase in yield which becomes increasingly high and more reliable with time. Regeneration of SOC in the agricultural soils of India provides an avenue through which the total food production will be improved and, at the same time, enhance the capacity to withstand climate change pressures and low the expenditure on inputs. Therefore, carbon sequestration in soil is not merely a service to the environment, but also fundamental agronomic policy to strengthen and build a sustainable productivity (Ma et al., 2023).

6. AGRICULTURAL PRACTICES FOR ENHANCING SOIL CARBON IN INDIA

Improving Soil Carbon Stocks in Indian Agriculture Management systems for Indian agriculture to increase biomass inputs and improve carbon stabilization in soil and minimize carbon losses. A large body of work of Indian and international long-term experiments has shown that some agronomic practices can considerably raise the soil organic carbon (SOC) while enhancing the soil health and productivity (Prusty et al., 2025). These practices are based on the agro-ecological realities, cropping systems, and socio-economic realities of the farmers (Kumara et al., 2023).

6.1. Conservation Agriculture Practices

Conservation agriculture (CA) is one of the best frameworks for carbon sequestration in soils. It is based on three key principles: minimum soil disturbance, permanent soil cover and diversified crop rotations. The lower degree of tillage decreases the physical breakup of aggregates in the soil and decelerates the oxidation of organic matter, which permits carbon to build up. Crop residue retention provides continuous sources of organic inputs, helps prevent soil surface erosion, helps moderate temperature and enhances moisture conservation. Crop diversification increases the underlying biomass with different root systems and promotes the activity of microbes which stabilize carbon. In case of Indian rice-wheat systems of Indo-Gangetic Plains, the adoption of zero tillage along with the residue retention has consistently led to higher levels of SOC accumulation than for conventional tillage. Benefits are similar in maize-based and rainfed systems in that reduced tillage can help improve soil aggregation and carbon protection in microaggregates.

6.2. Organic Farming and Crop Residue Management

The main ways through which organic farming systems help to increase SOC include regular use of farmyard manure, compost, green manure, crop residues and bio-fertilizer. These organic inputs dilute the labile and stable carbon pools, which enhance the microbes and enhance the structure of the soil. Indian agriculture is quite dependent on crop residue management. Existence of residues on the soil surface or in the soil enhances carbon contribution and decreases the erosion losses. Nevertheless, residue consumption is against livestock feed and domestic fuel requirements, and open burning of residues is rampant in most areas. These trade-offs need to be overcome to scale up residue based carbon management strategies.

6.3. Compost-Based inputs/Integrated Nutrient Management

Integrated Nutrient Management (INM) is an approach that involves organic additions to soil and use of chemical fertilizers in a balanced manner to maintain the soil fertility and carbon reserves. Organic inputs provide carbon and soil structure whereas mineral fertilisers are for high crop productivity to increase biomass return to soil. This symbiosis enables the maintenance of SOC at all times and to sustain nutrient requirements of intensive cropping systems. Composting, vermicomposting, enhanced manures and crop-based composting technologies add to the strengthening of soil carbon accumulation. Long-term experiments have been conducted in Indian soils that have demonstrated that INM systems have much higher SOC levels and yield stability than those systems relying solely on chemical fertilizers (Jat et al., 2023).

6.4. Perennial Production Systems and Agroforestry

Agroforestry provides one of the greatest potential for soil carbon sequestration in Indian landscape. Trees and perennial vegetation are the source of continuous organic inputs in the form of leaf litter, fine roots and root exudates. They have their deeper root systems which taking the carbon to the lower levels of the soil where decomposition occurs at a lower rate and the carbon is more stable. Agroforestry systems also promote microclimate control, soil erosion control, soil moisture retention and farm income diversification. Trees have been found to give great benefits to SOC, soil health and livelihood resiliency when planted along with crops and livestock in tribal and rainfed areas of India.

6.5. Biochar Implementation and New Carbon-Enhancing Practices

Biochar is a new strategy that is being considered as a way of storing carbon in soil over a long period of time, and a product of bio-pyrolysis of biomass in conditions of low oxygen levels. Biochar is very stable and capable of remaining in the soils over centuries. When used properly, it enhances his soil structure, nutrient retention, and habitat of microorganisms and immobilizes carbon in a form that is resistant over time. Other developing practices are the application of microbial inoculants, carbon-based soil conditioners, application of exact residue management, and regenerative agriculture models that focus on constant soil cover and biological activity. These methods were shown to be promising, but need to be properly validated region-specifically and economically, before large-scale implementation in India (Srinivasarao et al., 2021).

7. CHALLENGES AND KNOWLEDGE GAPS

Although the sequestration of carbon in the soil has been proved to be beneficial in improving the soil health and agricultural production, there are a number of technical, environmental, and socio-economic challenges that limit the large scale adoption of the soil carbon sequestration in the Indian agriculture. These limitations need to be solved to transform scientific potential into most practical and sustainable results (Selvi et al., 2025).

7.1. Limitations in Measurement, Monitoring and Verification

Among the greatest impediments to effective soil carbon management, the challenge of measuring and monitoring the soil organic carbon (SOC) changes is also a major problem. SOC is highly variable in space, even within a single field, and its assessment is therefore expensive and technically challenging. Conventional sampling of soil and analysis in the laboratory is time consuming and costly, which restricts their use for extensive monitoring programs. Additionally, most soil surveys concentrate on the upper layers (0-15 cm or 0-30 cm), but large quantities of carbon are stored in deeper layers of soil that are not often measured. Uncertainty in measurement makes developing systems of carbon accounting difficult and destroys the confidence of carbon credit schemes in agriculture. Reliable, low-cost and scalable monitoring, reporting, and verification (MRV) frameworks is still a big research agenda for India.

7.2. Problems of Regional Variability and Scaling

India's agro-ecological diversity implies that the land use management strategies for sequestering carbon in soil, which are successful in one area, may not be successful in another. Climate, soil texture, mineralogy, cropping patterns and biomass availability vary highly throughout the country, and as a result, sequestration potential and response to management practices vary greatly from region to region. The size of the farm, availability of resources and access to technology also limit the scaling up of SOC-enhancing practices. Institutional support is usually lacking to enable small hold farmers who control Indian agriculture to adopt measures like conservation agriculture, retention of residues or agro forestry without capital, machinery and risk buffering capacity.

7.3. Trade-offs with Food Security and Livelihoods

There are trade-offs that are part of soil carbon management and this directly impacts the livelihoods of the farmers. Crop residues, which are a significant source of soil carbon input, are also important for fodder (for livestock), fuel (for domestic use) and bedding. These necessary needs may become inconsistent with diverting residues to an improvement of soil especially in mixed crop-livestock systems. Practices that increase SOC may have the side-effect of initially decreasing yields or increasing labor demands and thus discourages the adoption among resource-poor farmers. The long-term sustainability objectives can be compromised without the supporting policies, extension services, and economical incentive.

7.4. Research Priorities of Indian Agriculture

A number of knowledge gaps need to be overcome in order to unlock the potential of soil carbon sequestration in India. These include:

- Quantification of region specific sequestration rates under various management systems;
- Long-term field experiments relating SOC changes to productivity, resilience and profitability;
- Development of low cost and highly accurate MRV technologies;
- Combination of soil carbon plans and climate adaptation, water management plans and nutrient-use efficiency plans;
- Enhancing extension systems to encourage centering adoption of carbon-building practices by the farmers.

Close up on these loopholes will enable soil carbon sequestration to transform into a viable idea into a sound pillar of sustainable agricultural development in India (Guvvala et al., 2024).

8. CONCLUSION

Soil carbon sequestration is one of the most powerful and practical ways of achieving sustainable soil health and long-term agricultural productivity in India. This review also notes that replenishment of soil organic carbon (SOC) is a climate mitigation measure, as well as a basic agronomic intervention, to improve soil organization, water and nutrient use sustainability, biological functioning and system resilience. The evidence synthesis of the agro-ecological conditions in India proves that soils with carbon-enriched soil constructions are always the ones that can sustain more and more stable agricultural produce especially as the climatic stress and resource demands keep on rising. Indian agriculture is grappling with depletion of soil carbon on a mass scale due to long years of intensive agricultural activities, removal of residue, erosion and imbalance in nutrient management. Nevertheless, the review also reveals that there is still a strong opportunity to turn around this trend using established management practices like conservation agriculture, integrated nutrient management, organic amendments, residue retention, agro forestry and emerging technologies of increase in carbon. Practices that are properly adjusted to local conditions and institutional frameworks will be able to enhance the output of farms, environmental sustainability, and livelihood security at the same time. Although promising, there is no way to scale the soil carbon sequestration process without confronting the main issues associated with measurement, spatial variation, socioeconomic trade-offs, and adoption barriers in smallholder farmers. The way ahead lies in enhancing long-term field studies, creating cost-effective and efficient monitoring tools, achieving carbon management and food security development and consolidating extension and policy tools to encourage sustainable soil management. Replenishment of the soil carbon stores must be noted as an Indian national agenda. Carbon management in soils will be an important component of climate, soil health and food security policies that will enable the development of resilient agricultural systems that will help sustain productivity and livelihoods under environmental and climatic change.

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