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**Review Paper**

# Agronomic approaches to achieving net carbon-negative emissions in Indian agroecosystems

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## ABSTRACT

India has a significant potential to store (C) in the diverse agroecosystems. In general, poor management techniques accelerate the terrestrial production and release of greenhouse gases (GHGs), which are also responsible for the variations in climate. India's primary sources of GHGs are the burning of fossil fuels in the production of industrial goods, agricultural activities, and related energy consumption. Majority of state loss its soil organic carbon (SOC) 0.2–0.6% during last 60 years. Whereas, the decline in SOC concentrations in the southeast coast, western coast (very humid), western coast (humid), and Nagpur region of India were 0.30, 2.46, 1.36, and 1.86%, respectively, during the same period. With a cumulative SOC loss of 133 Pg (Petagram=$10^{12}$ kg) C since the onset of agriculture, most agricultural soils worldwide have already lost 25–75% of their original SOC stock due to extractive farming practices. Globally, the technical potential of C sequestration is about 2.55-4.96 Pg C through the adaptation of best management practices, of which the potential of crop land is 0.4-1.2 Pg C. Therefore, to advance sustainability for India's food, nutrition, economy, and environmental security, the priority lies in restoring the SOC pool by upscaling agronomical best management practices, developing focused policies, and upscaling environment-friendly and economically viable agricultural systems. Several agronomic strategies can be used to lower carbon dioxide ($CO_2$) emissions and enable agriculture to achieve a potential net negative C emission from agroecosystems. Using no-till or reduced-till farming techniques with crop diversification can minimize soil disturbance and create a positive soil/ecosystem C budget. Restoring SOC stock and soil health can be achieved by cover cropping, green manuring, and applying farmyard manure, compost, vermicompost, and biochar. Optimising fertiliser uses through data analytics, crop waste recycling, and precision farming can achieve net negative C emissions. By combining crops and trees, agroforestry techniques help to capture the atmospheric $CO_2$, increase input and energy efficiency, and lower C emissions. To encourage farmers to participate in C credit programs through agronomic management, the Indian government at both the state and central levels has implemented measures to align existing natural, regenerative, and organic farming schemes and policies. By 2030, the demand for C credits is expected to increase by approximately 15 times, with the price per tonne of C credits, as of 2023, ranging from US$ 40 to 80. Therefore, this article is aimed at implementing viable plans for transforming agriculture from a problem to a part of the solution by adopting practices which achieve net C-negative emissions.

***Key words:*** Agroecosystem, Agronomic approaches, Soil organic carbon, Sustainable development goals

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Building resilience by soil conservation has become imperative for ensuring the accessibility of food, water, and energy for humanity because these can significantly improve adaptability to climate change (Mishra, 2014). Several campaigns and strategies have been implemented and brought together globally to prevent carbon dioxide ($CO_2$) emissions and enhance soil health through agronomical management. Sustainable agriculture measures and agronomical approaches such as growing improved crop varieties, maintaining compatible vegetative ground cover, recycling crop residues, reducing pesticide usage, minimizing tillage, *etc.,* must be utilized to manage soil functions and reduce $CO_2$ emission (Sherwood and

Uphoff, 2000). Many nations around the globe are establishing action plans to minimize risks of soil degradation while restoring the environment and improving agronomic productivity (Lal, 2012). Soil is a living entity because of the activity and species diversity of soil biota, which is driven by an optimal level of soil organic carbon (SOC) content. Most soils of South Asia have an SOC content of 0.1% to 0.5% (Jat *et al.,* 2022). When compared to uncultivated soils before the 1960s, the SOC content in the top 20 cm of soil in several states of India declined dramatically because of land misuse and poor soil management (Lal, 2013). To reverse the trend of declining SOC content, Government of India (GoI) has invested in maintaining soil fertility and minimizing degradation of soil health (Katyal and Chaudhari, 2021). Protection, restoration and sustainable management of soil health may contribute directly to maintaining resiliency against climate change, while sustaining food, water, and energy availability. The SOC content in soils of the agroecosystem in the plough layer is 2-4 g $kg^{-1}$ in the rice-wheat cropping system (RWCS) of the Indo-Gangetic plains (IGPs), which is significantly less than the threshold value of 15–20 g $kg^{-1}$ (Singh *et al.,* 2021). Unsustainable farming practices put SOC content at risk, leading to a decline in soil health (Swarup *et al.,* 2019). Thus, the research, development, and extension network must be strengthened while policymakers must implement policies in support of the best agronomical management (Davis *et al.,* 2019).

Emission of $CO_2$ from soils of agroecosystems is also driven by intensive tillage, mismanagement of agronomical approaches, and in-field burning of crop residues (Bhuvaneshwari *et al*., 2019). Thus, adoption of conservation agriculture (CA) measures (i.e., no-till, crop rotation, and retention of crop residues as mulch) is critical to restoring SOC stock (Meena *et al*., 2020a). An effective soil carbon (C) sequestration plan in India remains a work in progress. Enhancing soil health necessitates that farmers enhance agronomic productivity by adopting system-based CA (Reicosky, and Kassam, 2021) and producing more from less. Effectiveness of CA can be enhanced when used in conjunction with green manure, farmyard manure, compost, vermicompost, biochar, *etc.*, which improve soil health, restore SOC stock and increase productivity (Bhattacharya *et al.,* 2000).

Upscaling agronomical best management practices (ABMPs) can reduce emissions of GHGs, restore SOC stock, and minimize risks of anthropogenic climate change (Pinheiroc *et al.,* 2015). In this context, the GOI has introduced initiatives aimed at enhancing SOC sequestration. However, achieving these goals requires the implementation of policies which support the restoration of soil C stock by the adoption of site-specific ABMPs. Two interrelated variables that affect a nation's food, nutritional, environmental, and economic status are soil health and climate change. A large proportion of India's soils, however, are less productive because of low SOC stocks. Therefore, it becomes imperative that serious consideration must be given to India's nutritional security through SOC restoration. Several countries have implemented soil health restorative programs such as "4p 1000" initiative (Lal, 2015a), Re-carbonization of Soil (RECSOIL) (Lal, 2013), Global Assessment of SOC Sequestration Potential (GSOCseq) program, Save Organics in Soil (SOS), *etc.*, because of the increasing demand for climate-resilient agricultural management and the important role of organic material in the soil to achieve net negative emissions. This article is focused on the multiple initiatives that have been implemented in India to restore soil health, which include the National Mission on Sustainable Agriculture (NMSA), Paramparagat Krishi Vikas Yojana (PKVY), Soil Health Card Scheme, National Project on Organic Farming (NPOF), Soil Health Management (SHM) Scheme, *etc*., for C negative agriculture in India.

### *Soil organic carbon stock status of various soil orders in India*

Tables 1 and 2 show the SOC status of soils of India for major physiographic zones. The decline in SOC can be brought about by agricultural practices like intensive tillage in various soils (Tripathi *et al.,* 2020).

Furthermore, constant chemical treatments have the potential to decrease soil organic matter (SOM), deplete vital nutrients, and perturb the ecosystem (Kumar *et al.,* 2023; Kumar *et al.,* 2022). Soil degradation may impact long-term productivity in farming due to enhanced erosion, compaction, and reduced soil fertility (Lal, 2015a, 2015b). Farmers use intensive tillage techniques and pesticides to keep the soil free of weeds during the cultivation process. Although these techniques produce levelled land and facilitate machinery operation, they also expose the soil to the damaging effects of precipitation. Furthermore, the SOM content is decreasing, which may degrade the soil quality and reduce the production capacity (Xu *et al.,* 2019).

Deforestation and land conversion are frequent results of increasing agricultural land to fulfill the demands of intensive farming. When forests are cut down for agriculture, habitat is lost, C sequestration is decreased, and biodiversity is diminished. This shift in land use accelerates climate change, disrupts ecosystem services (ESs), and leads to resource depletion (Gibbs *et al.,* 2011; Hosonuma *et al.,* 2012). High-yielding crop varieties are also used in intensive agriculture, replacing conventional and regionally appropriate ones. Due to the loss of resilient and diverse crop genetic resources, this loss may cause genetic erosion.

**Table 1.** Carbon stock (in Pg = $10^{15}$g) distribution by order in Indian soils (Source: Modified from Bhattacharyya *et al.,* 2000; Pal *et al.,* 2018).

| Soil order | Soil depth (cm) | Carbon Stock (Pg) | | |
|---|---|---|---|---|
| | | SIC | SOC | TC |
| Vertisols | 0–30 | 1.07(26) | 2.59(27) | 3.66(27) |
| | 0–150 | 6.14(18) | 8.77(29) | 14.90(23) |
| Entisols | 0–30 | 0.89(21) | 0.62(6) | 1.51(11) |
| | 0–150 | 2.86(8) | 2.56(8) | 5.42(8) |
| Inceptisols | 0–30 | 0.62(15) | 2.17(23) | 2.79(20) |
| | 0–150 | 7.04(21) | 5.81(19) | 12.85(20) |
| Aridisols | 0–30 | 1.40(34) | 0.74(8) | 2.14(16) |
| | 0–150 | 13.40(39) | 2.02(7) | 14.42(24) |
| Alfisols | 0–30 | 0.16(4) | 3.14(33) | 3.30(24) |
| | 0–150 | 4.48(13) | 9.72(32) | 14.20(22) |
| Ultisols | 0–30 | 0.03 | 0.20(2) | 0.20(1) |
| | 0–150 | 0.04 | 0.55(2) | 0.55(1) |
| Mollisols | 0–30 | 0.03 | 0.09(1) | 0.09(1) |
| | 0–150 | 0.07(0.2) | 0.49(2) | 0.56(1) |
| Total | 0–30 | 4.14 | 9.55 | 13.69 |
| | 0–150 | 33.98 | 29.92 | 63.90 |

SIC: Soil inorganic carbon; SOC: Soil organic carbon; TC: Total carbon

**Table 2.** Soil organic carbon status (in %) – physiographic region of India. (*Source*: Modied from Bhattacharyya *et al.,* 2000a; Mandal and Sharda, 2011).

| S. No. | Physiographic regions | Soil organic carbon | Vegetation |
|---|---|---|---|
| 1. | Northern Mountains | 0.40–2.75 | Dry temperature, coniferous forest, moist temperature |
| 2. | The Great Plains | 0.40–2.8 | Tropical mixed deciduous forest |
| 3. | Peninsular plateau | 0.3–3.40 | Tropical dry deciduous thorn forest |
| 4. | Peninsular India | 0.04–2.31 | Mixed deciduous thorn forest |
| 5. | Plains of the islands and coastal plains | 0.28–1.70 | Littoral and swamps |

Crops that have experienced genetic erosion are less able to adapt to environmental stresses, diseases, and pests (Jarvis *et al.,* 2008; Tanksley and McCouch, 1997). Managing agroecosystems by employing ecological principles is one method to solve these problems.

One of the most important metrics for evaluating the health of the soil is SOC sequestration (Liptzin *et al.,* 2022). With a cumulative SOC loss of 133 Pg (Petagram $=10^{12}$ kg) C, the majority of agricultural soils worldwide have already lost 25–75% of their original SOC flux due to extractive cultivation practices (Lal, 2013). It is estimated that long-term use of extractive farming practices can decrease soil C stocks (Lal, 2013). The SOC pool in the top 40 cm depth of soils in India has been drastically reduced. Depending on the soil and previous land-use style, the amount of C loss varies from 10 to 30 Mg C $ha^{-1}$, becoming more prevalent in soils that are prone to salinization and erosion (Lal, 2015a).

The short-term impacts are generally significant, and the soil C pool may be affected by the agricultural ecosystem in the long run, even decades after farming is stopped (Das *et al.,* 2017; Solomon *et al.,* 2007). The initial C depletion was linked to reduced plant productivity, decreased production of biomass, reduced aggregation, impeded aeration, increased decomposition, and changed soil biological properties (Bhat *et al.,* 2019; Culman *et al.,* 2010). Soil aggregation can be decreased by cultivation, which can increase C loss and subsequently decrease the retention of new C additions (Six *et al.,* 2000)., A meta-analysis by Guo and Gifford (2002) found that changes in land use from native forest to cropland (42%) and plantation forest (13%), as well as from pasture to cropland (52%) and plantation (10%), were associated with a decrease in soil C content. The depletion of SOC was caused by substantial farming methods with a high rate of organic matter (OM) extraction, mineralization/oxidation, and soil erosion (Ram and Meena, 2014; Söderström *et al.,* 2014).

In contrast to uncultivated soils before the 1960s, the SOC concentration in the top 20 cm of soil in several Indian regions declined dramatically by the adoption of inappropriate cultivation practices (Lal, 2013). For example, Jenny and Raychaudhuri (2002) compiled data from several Indian provinces and observed that intensive agricultural practices resulted in a notable loss of SOC content (0–20 cm). The SOC content of soils in India's southeast coast, western coast (very humid), western coast (humid), and Nagpur region dropped to 0.30%, 2.46%, 1.36%, and 1.86%, respectively, when the soils were cultivated. The SOM content is an indicator of soil C sequestration as well as a marker of its persistence. In terrestrial ecosystems, the SOC is the largest C pool and is responsible for determining input use efficiency and soil quality (Meena *et al.,* 2017; Wiesmeier *et al.,* 2016). Thus, in rhizosphere zones, a desired level of SOC is 1.5% (Lal, 2013). Sustainable intensification may be a useful strategy for halting SOC loss caused by land misuse and soil mismanagement.

### *India's progress on a global scale for net carbon negative emissions*

After contemplating the impacts of the changing climate, the GOI launched a program in 2008 called the "National Action Plan on Climate Change (NAPCC)", which included eight missions. To identify climate change mitigation solutions, the NMEEE (National Mission for Enhanced Energy Efficiency) was founded under the NAPCC. Additionally, PAT (Perform, Achieve, and Trade) has the goal to cut emissions of $CO_2$ to roughly thirty billion metric tons under the NMEEE. The Paris Agreement contains a system to aid in GHG mitigation and encourage the Sustainable Development System (SDM) under Articles 6.4-7.7.

According to the Ministry of Power 2020, the most significant aspects of India's contributions to the UNFCCC (United Nations Framework Convention on Climate Change) are as follows:

- Promoting a healthful and environmentally conscious approach to existence that adheres to customs and principles.
- Promote fertilizer-saving and SOC-adding-based approaches like organic farming, natural farming, regenerative agriculture, etc.
- To select an environmentally conscious and kinder pathway towards the development of the economy.
- To decrease emissions 33-35% above 2020 levels by 2030.
- To discover and create afforestation as a new C storehouse that can eliminate 2.5-3 Pg (peta gram) of $CO_2$ equivalent.
- To propagate climate-smart techniques aimed at reducing the adverse impacts of climate change, particularly in areas like agricultural production and water resources.
- To obtain contributions from advanced countries towards minimizing C emissions.
- Collaborative research programs to quickly spread climate-smart technology throughout India's villages.

### *Net carbon negative emissions through agronomic interventions*

According to Nieder *et al*. (2018), SOC constitutes a single of the most significant components of the worldwide C cycle. Consequently, the current state of SOC within low-C-containing soil needs to be retained in harmony and increased wherever it is feasible to do so. According to Bengtsson *et al*. (2019), organic matter from soil serves as an essential in preserving soil fertility, biodiversity, and food security, besides other benefits associated with ecosystems. Restoring the SOC pool through the expansion of agronomical best management practices, the creation of targeted regulations, and the expansion of environmentally friendly and commercially successful agricultural systems are the top priorities for advancing sustainability for India's food, nutrition, economy, and environmental security. To reduce carbon dioxide ($CO_2$) emissions and help agriculture reach a potential net negative C emission from agroecosystems, several agronomic techniques can be employed. Crop variety combined with no-till or reduced-till farming methods can reduce soil disturbance and improve the soil/ecosystem C budget. Cover crops, green manuring, and the application of farmyard manure, compost, vermicompost, and biochar can all help restore SOC stock and soil health. Net negative C emissions can be attained by optimizing fertilizer uses through data analytics, crop waste recycling, and precision farming. Agroforestry methods, which combine crops and trees, reduce C emissions, improve input and energy efficiency, and help absorb $CO_2$ from the atmosphere. Additionally, $CO_2$ emissions can be minimized by organic or bio-based replacements.

### *Natural Farming*

Due to each of its four main components, *viz.* jeevamrutham, beejamrutham, acchadana (mulching), and whapasa (soil aeration), having been asserted to increase microbial activity and provide nitrogen (N)—through green mulching but also by increasing the accessibility of already existing topsoil N—natural cultivation has recently been advocated as a more beneficial farming practice to the environment than conventional farming as well as a cost-free system in India, potentially reducing fertilizer production requirement (Smith *et al.,* 2020). Biobased farming has been demonstrated by comparative life cycle analysis (LCA) to utilize 50–60% less water, 47–70% less energy, and create 55–85% fewer GHG emissions, which may promote the net-negative C emission (Rose *et al*., 2021). Masanobu Fukuoka established the natural agricultural method known as permaculture (Fukuoka 1985; Krebs and Bach 2018).

### *Manure Management*

Organic manuring is an essential element of permaculture; however, sadly, livestock and agricultural animals have been shown to release more GHGs than tractors. Fig. 1 illustrates efficient approaches to reducing net C emissions from agroecosystems by managing agronomic practices. A crucial approach for improving the retention of C in the soil is proper manure management. Organic manures sequester more SOC than chemical fertilizers, according to several long-term European experiments (Powlson *et al*., 2013). Due to its significant N concentration along with a low C-to-N ratio, organic manure decomposes quickly. However, because of its elevated C concentration, manure can raise SC levels, and many investigations have examined how manure application influences SOC stocks; some studies demonstrated either small or negative consequences, while others have shown increases in C (Gross and Glaser, 2021, Kaur *et al.,* 2023).

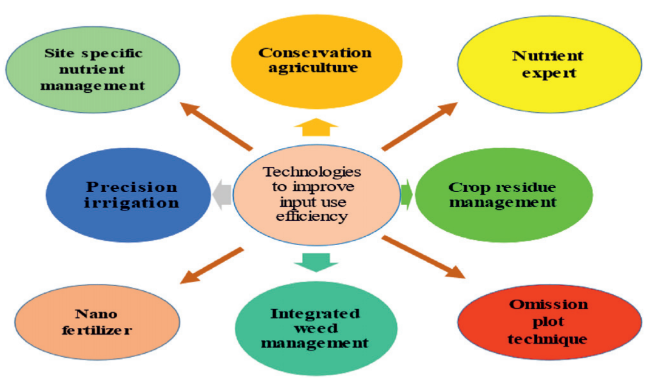


**Fig. 1.** Technological options for net carbon negative emissions

### *Guidelines for Crop Diversification Advancement*

Adequate and proper policy planning is essential to encourage crop diversification (Fig. 2). The policy ought to address the availability of infrastructure, supporting expenditures, advances in technology, and farmer education to help them choose alternative or highly profitable crops that are a good fit for their particular soil types. The government is currently looking for novel possibilities through crop diversification that are attractive and encourage C accumulation in agriculture to promote net-negative C emission.

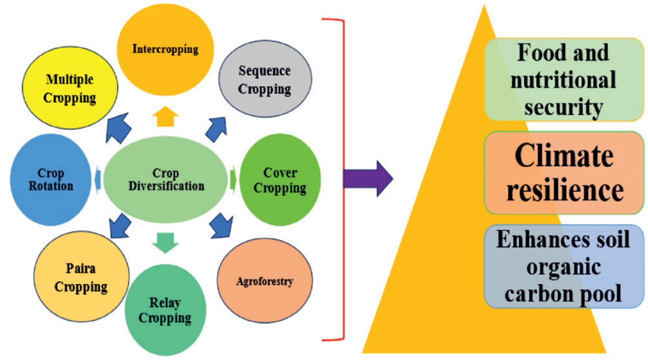


**Fig. 2.** Crop diversification towards achieving net carbon negative emissions

### *Fallow Management Strategies*

The need for environmentally friendly handling of the capture of C from soil increases as more agricultural land is set aside and turned back to the natural environment. Summer fallow (April to June), rice fallow (November to February), and dryland fallow (*Kharif* fallow in the absence of adequate rainfall or *Rabi* dormant due to a lack of residual moisture) are the three types of periods of fallow land in India. Approximately 82% of the 11 million hectares (ha) of fallow land in India can be found in the eastern states of West Bengal, Odisha, Jharkhand, Assam, Bihar, Chhattisgarh, Eastern Uttar Pradesh, *etc*. Karnataka, Tamil Nadu, and Andhra Pradesh make up the balance of the farmland in peninsular India (IIPR 2016). Employing these vacant, fallow acres for the establishment of pulses and oilseeds using appropriate methods of management has benefited them significantly from the development and execution of applicable policies. The Indian government has launched a commendable endeavour to locate promising locations for growing pulses and oilseeds. The nation's government has started screening, finding suitable crops and cultivars, agronomic management, and other promotional technologies in cooperation and partnership with foreign entities and groups.

### *Promoting Pulses in Rice-Based Systems*

Several types of pulses and oilseeds, such as lentil (*Lens culinaris)*, pea (*Pisum sativum)*, green gram (*Vigna radiate)*, chickpea (*Cicer arietinum*), black gram (*Vigna mungo*), pigeon pea (*Cajanus cajan*), Lathyrus (*Lathyrus aphaca*), mustard (*Brassica juncea*), sesame (*Sesamum indicum)*, peanut (*Arachis hypogaea*), sunflower (*Helianthus annuus)*, and linseed (*Linum usitatissimum*), are raised beside rice in large quantities. The government intends to widen the TRFA (Targeting Rice Fallow Areas) program in the rice-growing regions of the southern, northern, and Himalayan states through 2022, following well-informed criteria for support (MoA&FW 2019a). Intending to increase production and SOC levels in rice fallows, the federal government is promoting regions that can be utilized for pulse cultivation as a component of the National Food Security Mission-Pulses (NFSM-Pulses). Farmers are encouraged to grow pulses by establishing cluster demonstrations, propagating high-quality seeds, supplying enhanced versions of equipment, tools, and technologies, offering irrigation tools, and using additional tactics.

### *Managing Soil Erosion*

We must safeguard natural resources, maintain food security, and minimize damage to the environment to address the challenges caused by land degradation. When normal cultivation destroys nearly all of an area's surface macroflora, soils used for farming are subject to erosion. Assuming a 10% delivery ratio and an average content of 2–3% SOC, the overall quantity transferred annually by erosion is calculated to be 4.0–6.0 Pg C (Du *et al.*, 2019). Additionally, a significant proportion of $CO_2$ emissions occur through the breakdown of the soil's C stock and biomass (Hussain *et al*., 2021).

### *Industrial Waste Use as a Carbon Input for Cultivated Soil*

India has experienced explosive industrialization that has resulted in massive quantities of waste from manufacturing, particularly fuel gas, byproducts, and additional wastes that can be harmful to ecosystems (Yadav *et al*., 2019). Those waste products may nevertheless be judiciously employed as an adequate C source for regenerating SOC content. We cannot immediately decide on closing down industries if we want to lower the concentration of $CO_2$ in our atmosphere, because doing so will directly affect the national economy. So, according to (Yadav *et al*., 2019), waste from manufacturing might be processed into a C-based soil amendment. Additionally, microalgae can utilize concentration levels of $CO_2$ that occur in industrial wastes as well as having a rate of expansion and fixation of $CO_2$ efficiency much greater (*ca.* 10-50 times greater) than terrestrial plant species (Chiu *et al*., 2008; Tang *et al*., 2011). Microalgae may represent an excellent option for lowering atmospheric C levels within the framework of a long-term sustainable solution to global warming. According to (Yadav *et al*., 2007, 2015), biological methods are currently thought to have been the most effective for absorbing and storing $CO_2$ from flue gas and wastewater treated with microalgae. As a result, it will become the technique of choice for boosting the storage of $CO_2$ from industrial wastes across the country (Ugwu *et al*., 2008).

According to (Tang *et al*., 2011) and (Kumar *et al*., 2011), absorbing atmospheric $CO_2$ in biomass can be used sustainably for creating biodiesel, bioethanol, biohydrogen, or methane. India currently has no rules regarding using waste from industries as a source of C for soil. To efficiently utilize the conversion of waste from industries and ensure they become a valuable and safe C source for the environment, brainstorming and ideation at the ground level are needed**.**

### *Eradicating crop waste burning from agricultural fields to achieve net carbon-negative emissions*

In India, agricultural methods of cultivation create a lot of residues. The vast majority of crop remains are used for domestic purposes such as fuel, fodder, and numerous other applications, however, they still get burned annually without adequate supervision, which discharges particulate matter into the atmosphere (Bhuvaneshwari *et al*., 2019). Burning crop residue has a negative influence on soil characteristics, minerals, fertility, and microbial activity, which in turn decreases the soil's capacity to hold C and hurts the health and quality of the soil (Meena *et al*., 2019). Fig. 3 shows the technologies to help to net C negative emissions.

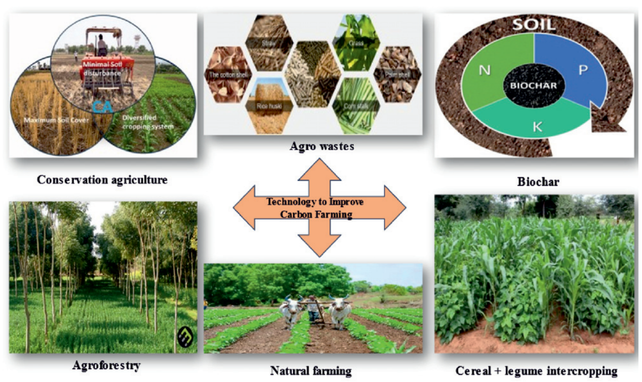


**Fig. 3.** Technologies to help to net carbon negative emissions

### *Carbon negative emissions can be achieved by converting crop residue into biochar*

Biochar is a material containing a C content of 35–60% and is generated through pyrolysis, gasification, and hydrothermal carbonization instead of leaking into the atmosphere. Bio-oil and syngas are the by-products of the manufacturing of biochar (Chowdhury *et al*., 2018). When biochar is spread to the ground, it increases the SOC pool, thereby enhancing the soil's physical, chemical, and biological qualities and restoring the health of the soil (Day *et al*., 2005; Sohi *et al*., 2010; Srinivasarao *et al*., 2012, 2013). Biochar is one of the best options for the retention of C in the soil and is an excellent option as a long-term C storage solution. Production at any size can be reasonably priced and environmentally friendly (Pratt and Moran, 2010). Soil C sequestration options for India are presented in Fig. 4.

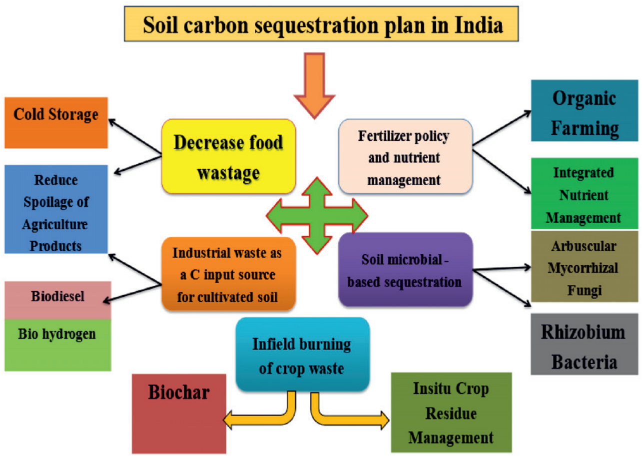


**Fig. 4.** Soil carbon sequestration plans for net carbon negative emissions in India

Through various extension infrastructures, such as Krishi Vigyan Kendras (Farm Advisory Service Scheme), the concept of biochar has gained widespread recognition among paddy farmers in Punjab, India. Biochar is an optimal material for enhancing SOC sequestration and reducing C-footprints due to its soft, porous, C-rich, fine-grained nature and extensive surface area (Srinivasarao *et al*., 2013; PAU, 2020). Given its role in promoting recalcitrant C storage in soil, biochar may help mitigate the adverse effects of global warming.

The application of biochar at a rate of 5 Mg (megagram) ha-1 has been sown to increase crop yields by 10% while also improving nitrogen-use efficiency (PAU 2020). Biochar, or "Biomass carbonization," converts harvestable biomass into more stable and resistant C rather than completely combusting it. As a byproduct of bioenergy production, biochar presents an innovative approach to terrestrial sequestration. Low-temperature pyrolysis, which heats biomass in an oxygen-limited environment, converts it into liquid and gaseous biofuels while also producing char-like materials due to the absence of complete combustion (Post *et al*., 2009). Through the clean process of biochar production – where heat and gaseous emissions are captured and utilized while C remains sequestered in the soil – it is possible to transform the 19.6 million tons of wheat and rice straw burned annually in the country into chemically stable C forms. Furthermore, recent advances in genomics provide unprecedented opportunities to identify the genes, enzymes, biochemical pathways, and regulatory systems that control rate-limiting C acquisition, transport, and storage. These discoveries can drive new strategies for enhancing terrestrial C sequestration across various crops, as summarized in Table 3.

To successfully integrate C-rich agricultural waste into the soil, municipal governments, local authorities, or farmers' associations can support them through education, awareness programs, and capacity-building initiatives (Bhuvaneshwari *et al*., 2019). Farmers can adopt a long-term approach to manage different cropping systems in India (Tables 4 & 5).

Implementing agronomic best management practices and creating targeted policies and plans for India's environmentally and financially sustainable agricultural systems are now essential. The government, at both state and federal levels, has taken action to integrate existing natural, regenerative, and organic agricultural schemes and policies to encourage farmers to participate in C credit programs through agronomic management. The existence and benefits of C farming are being communicated to all farmers who engage in C-credit-based farming as a source of income. The demand for C credits is expected to have grown by approximately 15-fold by 2030. As of 2023, the cost per tonne of C credits ranges from 40 to 80$. $CO_2$ emissions from crop fields can be reduced using various agronomic techniques. This can be achieved through reduced-till or no-till farming practices, which are suitable for various

**Table 3.** Different sources of biochar and its nutrient contents (*Source*: Hossain *et al.,* 2020)

| Biochar source | Carbon (%) | Nitrogen (%) | Phosphorus (%) | Potassium (%) |
|---|---|---|---|---|
| Rice husk | 39.90 | 0.54 | 0.16 | 0.58 |
| Wheat straw | 52.12 | 0.2 | 0.27 | 0.25 |
| Barley straw | 71.50 | 1.3 | 0.34 | 0.42 |
| Cornstalk | 70.50 | 0.69 | 0.24 | 1.61 |
| Sugarcane bagasse | 63.27 | 0.67 | 0.07 | 0.78 |
| Sewage and sludge | 34.56 | 2.7 | 1.7 | 0.26 |
| Castor stalk | 43.18 | 1.57 | 0.22 | 0.62 |

**Table 4.** Carbon sequestration rate in different cropping systems in India.

| S. No. | Crops/ cropping system | Carbon sequestration (Mg C/ha/yr) | References |
|---|---|---|---|
| 1. | Rice–wheat | 4.92 – 7.43 | Meena and Pradhan (2023) |
| 2. | Poplar-based agroforestry system | 1.96 – 9.24 | Sharma *et al.* (2015) |
| 3. | Maize-based system | 0.21 – 0.51 | Yadav *et al.* (2021) |
| 4. | Maize-wheat-cowpea | 2.09 – 2.22 | Purakayastha *et al.* (2008) |
| 5. | Maize–wheat–maize–chickpea | 7.48 | Venkatesh *et al.* (2012) |
| 6. | Maize–wheat–mungbean | 8.11 | Venkatesh *et al.* (2012) |
| 7. | Pigeonpea–wheat | 7.67 | Venkatesh *et al.* (2012) |
| 8. | Soybean–corn | 0.68 | Kumar *et al.* (2018) |
| 9. | Soybean–sunflower | 0.57 | Kumar *et al.* (2018) |
| 10. | Soybean–sun hemp | 0.79 | Kumar *et al.* (2018) |

**Table 5.** Carbon sequestration potential of different climate-smart practices across the crops and cropping systems

| S. No. | Climate-smart practices | Crops/ cropping system | Carbon sequestration (Mg C/ha/yr) | References |
|---|---|---|---|---|
| 1. | Conservation agriculture | Rice-wheat | 1.1 | Sapkota *et al.* (2017) |
| 2. | No-tillage | – | 0.30-0.57 | Minasny *et al.* (2017); West and Post (2002) |
| 3. | Residue retention | – | 0.4 | Yadav *et al.* (2019) |
| 4. | Crop rotation | – | 0.2 | Minasny *et al.* (2017); West and Post (2002) |
| 5. | Cover cropping | – | 0.21-0.56 | Jian *et al.* (2020); McClelland *et al.* (2021); Poeplau and Don (2015) |
| 6. | Green manuring | Rice | 0.442 | GAO *et al.* (2023) |
| 7. | Bulky manures/compost | Rice–wheat | 0.08–0.98/ | Duxbury (2001) |
| 8. | Biochar application | - | 0.7 Mg C/t | Galinato *et al.* (2011) |
| 9. | Restore soil fertility *via* integrated nutrient management on cropland and grasslands. | - | 0.33/ | Mani *et al.* (2011) |
| 10. | Improved nutrient management | - | 0.050–0.15 | Gill (2014) |
| 11. | Agroforestry system | - | 1.5–3.5 | Montagnini and Nair (2004) |
| 12. | Integrated crop-livestock | Low/moderate grazing intensity | 0.96 | Assmann *et al.* (2014) |
| 14. | Improved grazing management | - | 0.35 | Paustian *et al.* (2001) |

crop varieties and minimize soil disturbance. The application of farmyard manure, compost, vermicompost, biochar, cover crops, and green manure can improve soil health and enhance C sequestration. C emissions can be reduced by using precision farming, crop residue recycling, and data analytics for optimized fertilizer use. Additionally, using sustainable fertilizers, such as organic or bio-based alternatives, can lower $CO_2$ emissions. Agroforestry systems, which integrate crops and trees, help absorb $CO_2$ from the atmosphere and reduce C emissions by improving input and energy efficiency.

### *Way forward*

The effective application of the aforementioned innovations and practices is crucial in the 21$^{st}$ century to ensure sufficient food production for the nation's growing population without negatively affecting the natural ecosystem. Therefore, raising awareness among farmers and other stakeholders is essential. With its extensive nationwide network, the National Agricultural Research System (NARES) is well-equipped to achieve net C-negative emissions through the effective application of agronomic approaches and policies in the coming years. Such approaches will also help the nation adapt to the potential effects of climate change.

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