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Chapter 3

Carbon Neutral Agriculture - Prospects & Challenges

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Abstract

Agriculture is a significant contributor to global greenhouse gas (GHG) emissions, accounting for about 24 percent worldwide and nearly 17.6 percent of total net CO_2 equivalent emissions in India. Major sources of emissions include improper soil and manure management, enteric fermentation from livestock, flooded rice cultivation, crop residue burning, and excessive use of nitrogenous fertilizers. Promoting carbon neutral agriculture is therefore essential to mitigate climate change impacts. Carbon neutral agriculture refers to achieving a net-zero balance of greenhouse gas emissions from farming systems through carbon sequestration and improved management practices. Several agronomic interventions such as conservation agriculture, balanced nutrient management, cover cropping, improved water management, soil and biodiversity conservation, and agroforestry play a crucial role in enhancing soil organic carbon (SOC) storage and reducing GHG emissions. Practices viz., alternate wetting and drying in rice cultivation, proper manure management, and inclusion of cover crops further contribute to lowering emissions while improving soil health and productivity. Although various government schemes promote climate-smart agricultural practices, the transition to carbon neutral agriculture in India faces challenges such as high initial investment, lack of infrastructure, technical constraints, and risks in rainfed regions. Therefore, strong policy support, technological innovations, and targeted investments are essential to facilitate the adoption of carbon neutral farming systems and ensure sustainable agricultural development.

Keywords: Carbon neutral agriculture, Carbon sequestration, Greenhouse gas emissions, Soil organic carbon.

Introduction

Agriculture accounts for nearly 24 percent of global greenhouse gas (GHG) emissions, while in India the sector contributes about 17.6 percent of the total net CO_2 equivalent emissions. Approximately 50 percent of India's methane emissions and a significant proportion of nitrous oxide emissions originate from agriculture. The major sources of emissions in Indian agriculture include enteric fermentation from livestock, rice cultivation, manure management, crop residue burning, application of nitrogenous fertilizers, and post-harvest ploughing, which exposes soil carbon to the atmosphere through increased aeration.

Achieving carbon neutrality in Indian soils is a major challenge. Productive agricultural land is increasingly being diverted to non-agricultural uses due to urbanization, industrialization, and other developmental activities, while cultivation is often extended to marginal and degraded lands. Moreover, increasing soil organic carbon (SOC) is difficult under tropical climatic conditions because the high temperature and moisture accelerate decomposition rates. According to a United Nations report, India is expected to become the most populous country in the world, adding about 273 million people between 2019 and 2050. This rapid population growth will place enormous pressure on natural resources, particularly soil and water, to meet rising food demands. Intensive exploitation of natural resources combined with continuous cultivation may lead to higher GHG emissions, declining agricultural productivity, land degradation, and reduced factor productivity in major cropping systems. In addition, changes in rainfall patterns and rising temperatures due to climate change make fertile topsoil increasingly vulnerable to degradation.

Climate change and food security have emerged as two of the most critical global challenges. Since the 19th century, the average global temperature has increased by about 0.9°C as a result of GHG emissions from various anthropogenic activities. Projections indicate that the temperature may increase by 1.5°C or more by 2050, which could intensify extreme weather events such as cloudbursts, floods, droughts, and heatwaves across the world.

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India has voluntarily committed to reducing the emissions intensity of its economy, which requires substantial mitigation efforts across different sectors, including agriculture. Low-carbon development pathways provide opportunities to reduce GHG emissions while sustaining growth. The agricultural sector can contribute significantly to this goal by adopting a systems-based "climate-smart agriculture" approach, which involves implementing technologies and practices that enhance productivity and farmers' income while reducing GHG emissions, thereby also creating opportunities in emerging carbon markets.

Carbon neutrality and carbon neutral agriculture

Carbon neutrality refers to balancing carbon dioxide emissions through carbon capture, storage, and other mitigation measures so that the net greenhouse gas (GHG) emissions become zero within a given period (Wu et al., 2022) [1]. The concept gained global attention after being introduced in Samsoe Island, Denmark in 1997, and has since been adopted across various sectors. In 2013, the International Air Transport Association proposed achieving carbon neutrality in the aviation sector by 2020, marking one of the first formal sectoral commitments toward this goal. The Paris Agreement aims to limit global warming to 1.5°C above pre-industrial levels, and according to the IPCC, achieving this objective requires global carbon neutrality by the mid-21st century. However, the UNEP Emissions Gap Report (2019) highlights a substantial gap between current national commitments and the emission reductions required to meet the 1.5°C target. India, along with several other countries, has announced long-term carbon neutrality goals, but progress remains challenging due to continued reliance on coal-based energy and slow expansion of clean energy sectors.

The role of agriculture and rural landscapes is crucial in achieving carbon neutrality. Carbon-neutral agriculture refers to maintaining a net-zero balance of all greenhouse gas emissions from farming activities when expressed as CO_2 equivalents. Agriculture contributes significantly to global GHG emissions through crop production practices, livestock enteric fermentation, manure management, and land-use changes. Improving agricultural management practices can therefore play a vital role in mitigating climate change. Forests and vegetation cover strongly influence soil carbon levels, while deforestation alters hydrological systems and land-use patterns. According to the Food and Agriculture Organization (FAO), agriculture, forestry and other land-use sectors account for about 24 percent of global GHG emissions, with livestock alone contributing 7.1 gigatons CO_2-equivalent annually (about 14.5 percent of anthropogenic emissions). At the same time, forests provide significant opportunities for carbon sequestration, thereby contributing to the reduction of global warming.

Scope of carbon sequestration in agriculture

An increase of 1 percent in soil organic carbon (SOC) in one acre of land is equivalent to storing about 18 metric tonnes of CO in the soil. It is estimated that increasing soil carbon by 0.4 percent annually in the top 30 - 40 cm of soil could remove approximately 3 - 4 gigatonnes of carbon from the atmosphere, improve soil health, and potentially halt the annual rise in atmospheric CO. Such an increase in soil carbon could also enhance crop yields by about 1.3 percent. Therefore, agriculture particularly agricultural soils plays a crucial role in addressing both food security and climate change. Adoption of scientifically managed agricultural practices can significantly contribute to the mitigation of greenhouse gas (GHG) emissions.

Several interventions can promote low-carbon agriculture, including no-till or minimum tillage systems, which reduce fuel consumption and tillage costs; sustainable forest management; introduction of improved livestock breeds to increase productivity while reducing herd size; and utilization of livestock waste for biogas production, which lowers methane emissions and provides renewable energy for household use. Additionally, mechanisms such as carbon credits and the development of domestic carbon markets can support the transition towards low-carbon agricultural systems.

Carbon farming, also known as soil carbon sequestration, involves adopting agricultural practices that remove excess carbon from the atmosphere and store it in soils. This process enhances soil fertility, nutrient retention, and crop productivity, thereby contributing to global food and nutrition security. Plants absorb atmospheric carbon dioxide during photosynthesis and convert it into stable forms of carbon that can be stored in soil through direct or indirect processes. However, several conventional agricultural practices such as excessive tillage, unscientific ploughing, overgrazing, and the use of fossil-fuel-based agrochemicals can accelerate the release of stored carbon back into the atmosphere. For carbon farming to be effective, carbon sequestration through improved land management must exceed the carbon losses resulting from agricultural activities.

Agronomic measures promoting carbon neutral agriculture

- Conservation agriculture
- Nutrient management
- Cover cropping
- Water management
- Soil and biodiversity conservation
- Agroforestry

Conservation Agriculture

Conservation Agriculture (CA) is a sustainable farming approach that helps prevent the loss of arable land while restoring degraded soils. It is based on three key principles: minimum soil disturbance (no-till or reduced tillage), permanent soil cover through crop residues, and crop diversification. These practices enhance biodiversity and support natural biological processes both above and below the soil surface, leading to improved water and nutrient use efficiency and stable crop productivity. The principles of CA are universally applicable across different agricultural systems, although the specific practices may vary depending on local conditions. Under this system, mechanical soil disturbance is minimized or avoided, and crop residues are retained on the soil surface to protect and enrich the soil. External inputs such as agrochemicals and plant nutrients, whether mineral or organic, are applied judiciously so that they do not disrupt soil biological activity and ecosystem functions (Mandal et al., 2020) [2].

Role of conservation tillage in C neutral agriculture

Soil carbon sequestration is essential for restoring soil fertility, as carbon plays a key role in maintaining soil quality. In India, the tropical and subtropical climate, along with conventional tillage and practices such as crop residue burning, limits the buildup of soil organic carbon (SOC). Conservation agriculture practices, particularly zero tillage (ZT) and residue retention, have been shown to enhance soil carbon content over the long term.

For instance, in North India, when cotton–wheat systems were grown under conservation agriculture, ZT with bed planting and ZT with flat planting recorded 28 and 26 percent higher SOC stocks, respectively, compared to conventional tillage with bed planting in the 0–5 cm soil layer (Das et al., 2013) [3]. Similarly, in Eastern India, after seven years of conservation agriculture practices, adoption of a DSR–ZT wheat–ZT moong bean system with full residue retention resulted in the highest SOC stock of 48 Mg C ha^{-1}, which was 15 percent higher than the farmer's practice in the 0–30 cm soil layer (Samal et al., 2017) [4]. Soil carbon accumulation under conservation tillage is generally more pronounced in the topsoil layer (0–5 cm) irrespective of soil type and climate (Veloso et al., 2020) [5].

Yadav et al. (2017) [6] reported that a double rice cropping system with reduced tillage, integrated nutrient management and 30 percent residue retention recorded the highest carbon accumulation and sequestration rate compared to other treatments in the Eastern Himalayan region. In a rice - mustard cropping system, higher SOC sequestration, SOC pools, carbon sequestration rate and carbon retention efficiency were observed under zero tillage with residue retention and mulching compared with conventional tillage with residue incorporation and no mulching (Yadav et al., 2019) [7]. In addition, growing cowpea as a cover crop during the pre-rainy season was found to double the rate of carbon sequestration.

Table 1: Effect of conventional and conservation tillage in storage of soil organic carbon

Soil depth (cm)	Conventional tillage	Conservation tillage
	Soil organic carbon (Mg ha^{-1})	
0-5	5.7	6.9
0-15	5.4	7.6
0-30	29.0	29.9

Crop residue mulching (CRM) to promote C neutral agriculture

Crop residue burning has become a recurring annual practice in the densely populated agricultural regions of India, China, and Southeast Asia. Among the top ten CO_2-emitting countries, India ranks second after China Figure 1 (FAO, 2019) [8]. According to the Indian Agricultural Research Institute (IARI), about 14 million tonnes (Mt) out of the 22 Mt of rice stubble produced annually in India nearly 63.6% are burned in the fields. The states of Haryana and Punjab, two major agricultural regions of the country, together account for nearly 48% of this total.

Several factors drive the practice of crop residue burning, including increased residue generation due to higher crop yields, scarcity of labour, the limited time gap between harvesting of the monsoon crop and sowing of the winter crop, lack of suitable residue management technologies, the low nutritional value of rice straw, financial constraints faced by farmers, social influences, and limited awareness regarding the public health impacts of residue burning.

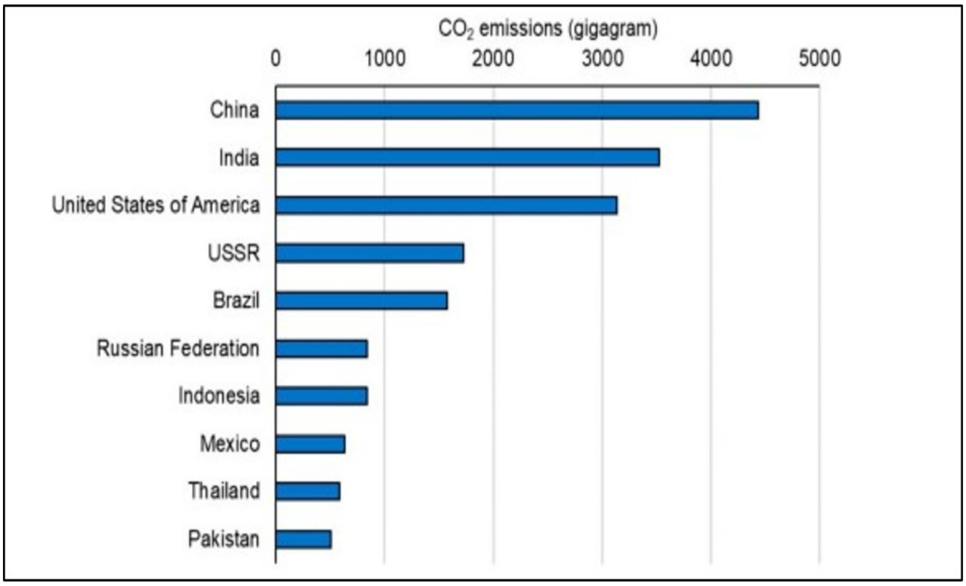

Figure 1: Top 10 CO_2 emitting countries according to crop residue burning (FAO, 2019) [8]

Crop residue incorporation into soil is an important agricultural management practice. Crop residues supply organic carbon (C) and nitrogen (N) to the soil, which helps maintain or enhance soil nutrient stocks and thereby improves soil health and crop productivity. However, the incorporation of residues can also lead to the emission of environmentally significant reactive gaseous forms of nitrogen. These include nitrous oxide (N_2O), a potent greenhouse gas; nitric oxide (NO), which contributes to tropospheric ozone depletion; and ammonia (NH_3) and nitrate (NO_3^-), which can form aerosols and cause eutrophication, with nitrate also having the potential to leach into water resources.

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Retention of crop residues on the soil surface can significantly reduce topsoil loss by about 30 percent. In addition, crop residue mulching increases the total carbon input in the 0–15 cm plough layer, contributing approximately 9.78 Mg C ha^{-1} yr^{-1} (Janz et al., 2022) [9].

Role of pulse crops in C sequestration

Pulses or food legumes are an important component of crop diversification because of their unique characteristics such as short duration, deep root systems, and lower dependence on mineral nitrogen. As a result, they serve as an important complement to cereal crops. Pulses are also well suited for conservation agriculture, particularly for the components of soil cover and crop rotation, either as a standing crop or through the residues they leave behind.

Legume-based crop rotations offer several advantages over continuous cereal-based systems (Mondal et al., 2021) [10] Figure 2. Therefore, diversification of exhaustive cereal–cereal systems is widely recommended. Pulses are considered an ideal choice for such diversification because of their short duration, seasonal flexibility, ability to fix atmospheric nitrogen (N_2), and deep root systems, which complement cereal crops effectively. Incorporating pulses as intercrops or as a component of cropping systems can significantly improve soil quality and enhance the overall sustainability of the production system.

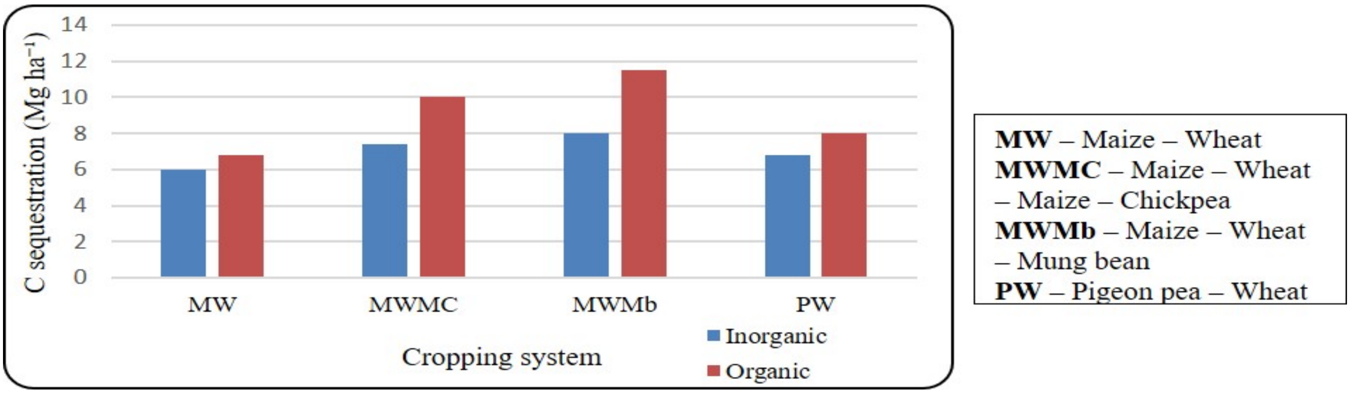
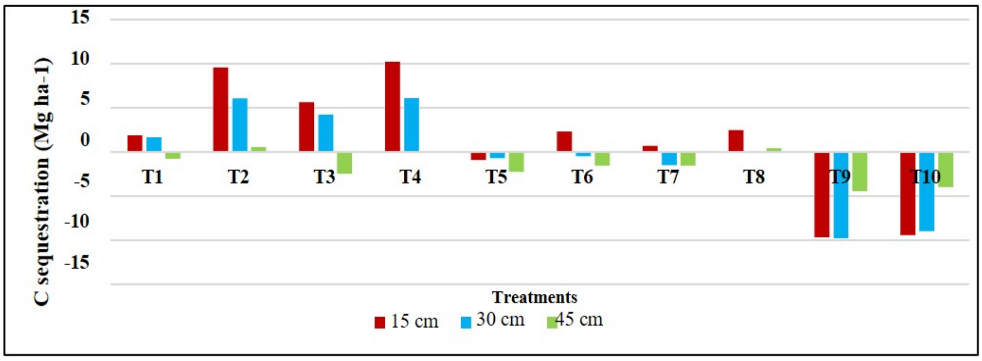


Figure 2: Role of pulses C sequestration in different cropping systems (Mondal et al., 2021) [10]

Conservation agriculture on carbon sequestration in soil



T1- Direct seeded rice in flat bed + BM – okra + GM - cowpea	T6- Direct seeded rice in raised bed + BM – okra + CRM - cowpea
T2-Direct seeded rice in flat bed + BM – okra + CRM - cowpea	T7-Direct seeded rice in raised bed + GM – okra + GM - cowpea
T3-Direct seeded rice in flat bed + GM – okra + GM - cowpea	T8-Direct seeded rice in raised bed + GM – okra + CRM - cowpea
T4-Direct seeded rice in flat bed + GM – okra + CRM - cowpea	T9-Direct seeded rice in flat bed – okra - cowpea
T5-Direct seeded rice in raised bed + BM – okra + GM – cowpea	T10-Direct seeded rice in raised bed – okra - cowpea
BM – Brown manuring, GM – Green manuring,	CRM – Crop residue mulching

Figure 3: Effect of conservation agriculture on C sequestration in soil (Durga, 2020) [11]

Conservation agriculture is based on three fundamental principles: minimum soil disturbance (minimum tillage), crop rotation, and the use of crop residues as mulch. Adoption of these practices helps improve crop productivity, enhance carbon sequestration, and reduce greenhouse gas (GHG) emissions. Conservation agriculture also increases soil organic carbon content, thereby contributing to greater carbon sequestration in soils.

A study conducted at Kerala Agricultural University compared different conservation tillage practices with conventional tillage systems Figure 3. Durga (2020) [11] reported that a rice –okra - cowpea cropping system under conservation agriculture practices recorded higher carbon sequestration than a rice – okra - fallow cropping system managed under conventional practices without conservation agriculture.

Nutrient management

Balanced fertilization with organic and inorganic fertilizers

In India, farmers often adopt both balanced and imbalanced fertilization practices for crop production. Soil carbon (C) sequestration is indirectly influenced by these practices through their effects on crop growth and productivity. Studies have shown that the proportion of rhizodeposition carbon contributing to below-ground carbon inputs through roots and rhizodeposition averages between 54 percent and 63 percent in cereal crops (Hirte et al., 2018) [12].

Several researchers have reported an apparent increase in soil organic carbon (SOC) stocks under balanced fertilization involving both organic and inorganic nutrient sources. This increase is mainly attributed to greater additions of organic carbon through plant residues and root biomass in soils, which result from higher crop yields under balanced fertilization (Mandal et al., 2020) [2]. However, the accumulation of SOC varies depending on ecological conditions, soil type, and regional climate. Therefore, cropping systems should include crops capable of producing higher amounts of residues and root biomass in order to enhance net carbon sequestration in the soil.

Mandal et al. (2020) [2] also reported that the rate of soil organic carbon (SOC) accumulation was disproportionately higher in certain cropping systems compared to the level of carbon inputs they received. For instance, despite having similar residue carbon inputs in the Rice–Wheat–Fallow (3.33 Mg ha^{-1} yr^{-1}) and Rice – Fallow - Berseem (3.17 Mg ha^{-1} yr^{-1}) systems, the annual rate of carbon build-up in the Rice–Wheat–Fallow (0.27 Mg ha^{-1} yr^{-1}) was more than double that of the Rice – Fallow - Berseem (0.13 Mg ha^{-1} yr^{-1}) Table 2.

This difference may be attributed to the faster decomposition of organic matter caused by the higher nitrogen content in the residues of crops such as berseem (2.6%) and jute (1.8%), along with their lower lipid and lignin contents in the Rice – Fallow - Berseem and Rice – Wheat - Jute systems. These findings indicate that not only the quantity but also the quality of crop residues plays a crucial role in regulating SOC accumulation in soils. Crop residues from rice and wheat, which generally have lower nitrogen content, are likely to be more effective for carbon sequestration compared to residues from crops such as berseem and jute that contain higher nitrogen levels.

Table 2: Effects of balanced fertilization (NPK and NPK+FYM or compost) on C build up in soils under different cropping systems

Cropping system	**C buildup over unfertilized control (%) – NPK**	**C buildup over unfertilized control (%) – NPK+ FYM/Compost**	**Rate of C build-up (Mg C ha^{-1} $soil^{-1}$ yr^{-1}) – NPK**	**Rate of C build-up (Mg C ha^{-1} $soil^{-1}$ yr^{-1}) – NPK+ FYM/Compost**
Rice - mustard - sesame	51.8	55.7	1.91	2.05
Rice - wheat - fallow	16.8	23.4	0.27	0.37
Rice - fallow - berseem	9.3	24.7	0.13	0.36
Rice - wheat - jute	14.9	32.3	0.11	0.25
Rice - fallow - rice*	33.5	54.8	0.28	0.45
Mean	25.2	38.2	0.54	0.70

FYM – Farmyard manure, * Compost was used

According to Ghosh et al. (2021) [13], incorporation of rice straw along with NPK fertilizers increased the active carbon pool, passive carbon pool, and total organic carbon in the soil. This was followed by the application of vermicompost with NPK, which showed results comparable to the incorporation of gliricidia leaves along with NPK Figure 4. The study indicated significant variations in organic carbon fractions under different organic and inorganic nutrient management practices across treatments.

Greater increases in soil organic carbon (SOC) were observed in long-term experiments involving the application of organic manures. Trivedi et al. (2020) [14] also reported a higher rate of carbon accumulation when fertilizers were applied in combination with lime Figure 5. The increase in labile carbon in FYMPK and FYMPKL plots may be attributed to the addition of well-decomposed farmyard manure and the higher rate of organic matter decomposition in the surface soil layer under the prevailing subtropical climatic conditions.

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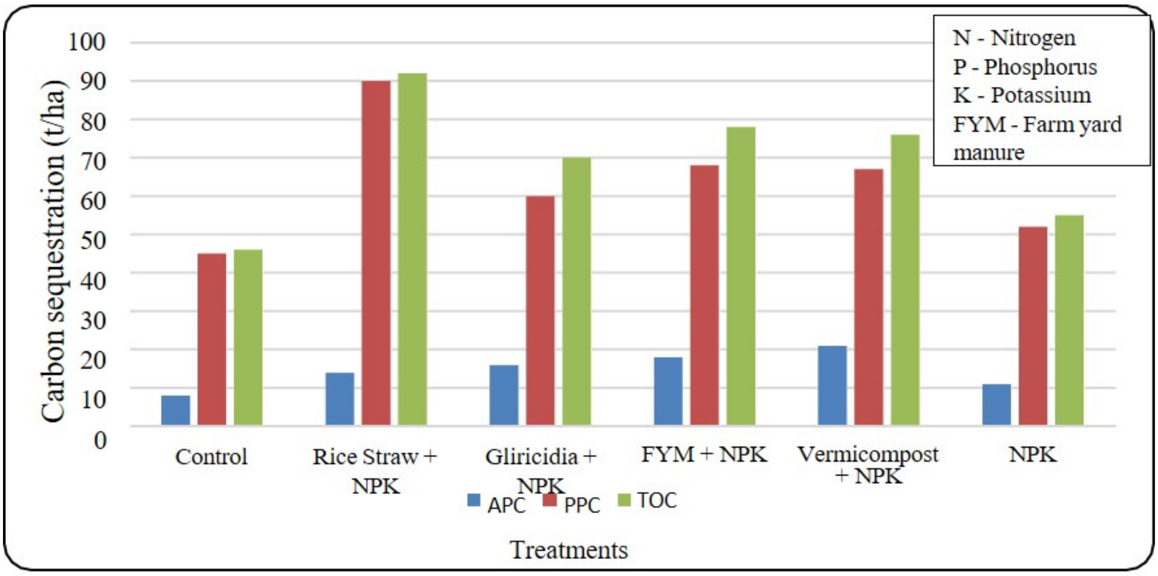

Figure 4: Effects of treatments on carbon sequestration in terms of total organic carbon (TOC), passive pool of carbon (PPC) and active pool of carbon (APC)

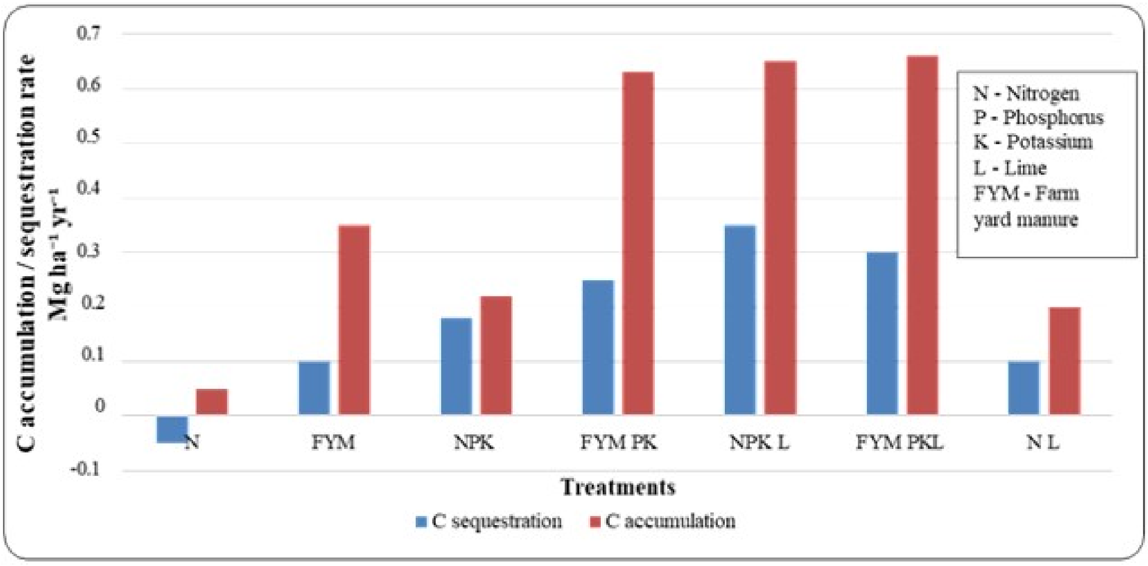

Figure 5: Effect of balanced fertilization and liming on C accumulation and C sequestration (Trivedi et al., 2020) [14]

Urea deep placement (UDP) technology

Urea deep placement (UDP) is a simple and field-tested nutrient management technology developed and validated by the International Fertilizer Development Center (IFDC) along with several research organizations in Asia and Africa. It is particularly suitable for smallholder farming systems. With the adoption of UDP, rice farmers can achieve yield increases of about 15–20% while using nearly one-third less fertilizer.

The technology involves the placement of larger urea granules or briquettes (1–3 g each) at a depth of about 7–10 cm below the soil surface, close to the root zone of the crop. Unlike conventional surface application of prilled or granular urea, which requires two to three applications during the crop season, urea briquettes in UDP are applied only once. This method ensures a sustained supply of nitrogen to the crop throughout its growth period Figure 6. As a result, plants are able to utilize a greater proportion of the applied nutrients, leading to improved crop yields and reduced production costs for farmers. UDP technology was developed by IFDC through research programs aimed at minimizing nitrogen losses and enhancing the efficiency of nitrogen fertilizer use by crops.

Livestock manure is an important source of greenhouse gas (GHG) emissions, primarily in the form of methane (CH_4) and nitrous oxide (N_2O). These emissions are biogenic in nature and are influenced by the characteristics of the manure, meaning that emission levels can be modified through appropriate handling, treatment, and storage practices. Livestock production systems vary widely across the world, and consequently the potential for GHG mitigation also differs. In general, strategies that conserve nutrients in manure for crop production tend to simultaneously reduce GHG emissions.

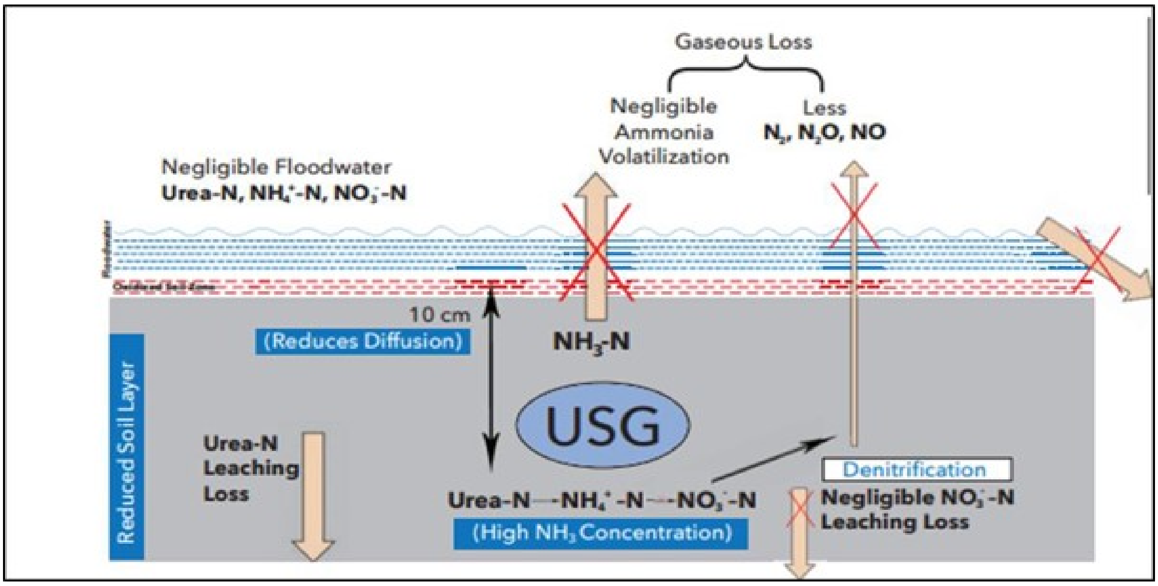

Figure 6: Effect of UDP in reducing losses and increasing soil N status

Manure management to reduce GHGs emission

Livestock urine and manure can produce significant amounts of methane and nitrous oxide when they decompose under anaerobic conditions. Nitrous oxide is mainly formed during the nitrification and denitrification processes of nitrogen present in livestock waste. Such anaerobic conditions frequently occur when manure is stored in large heaps or in settlement ponds used to manage waste from large numbers of animals kept in confined production systems.

Methane has a global warming potential about 25 times greater than carbon dioxide, while nitrous oxide has nearly 300 times greater warming potential. Ruminant animals excrete approximately 75–95% of the nitrogen they consume. When ruminants graze on lush spring pastures, they often ingest protein in excess of their nutritional requirement but remain limited by energy intake. This leads to higher concentrations of ruminal ammonia, which are subsequently excreted in the urine as urea. Nitrous oxide emissions from ruminant production systems can be reduced by maintaining a balanced protein-to-energy ratio in animal diets (Peterson et al., 2019) [15].

Measures to reduce GHG emissions from livestock include:

- Improving feed digestibility
- Use of feed additives
- Composting of manure
- Adoption of on-farm biogas technology
- Providing surface cover for urine and manure storage
- Maintaining optimum manure storage temperature
- Using forage with a higher energy-to-protein ratio

Cover crops in C neutral agriculture

Cover crops are an effective strategy for enhancing soil carbon sequestration. The biomass produced by their roots and shoots supports soil organisms such as bacteria, fungi, and earthworms, which in turn contributes to the gradual buildup of soil carbon. Increasing carbon inputs to the soil is a key pathway for improving soil carbon storage, and the inclusion of cover crops in cropping systems is therefore recommended as a management practice to increase soil organic carbon (SOC) stocks.

Apart from supplying carbon inputs, cover crops provide several agroecosystem benefits. They help reduce nitrogen losses through leaching, improve the productivity of subsequent crops, and enhance overall soil quality. Long-term studies have demonstrated that cover crops have significant potential to increase soil organic carbon stocks and contribute to carbon sequestration. Additionally, they help control soil erosion, regulate soil moisture, and suppress the growth of soil-borne diseases, pests, and weeds.

Residue management also strongly influences soil organic carbon levels. Removal of more than 50 percent of crop residues can reduce SOC stocks by approximately 0.87 Mg ha^{-1} yr^{-1}, whereas removal of less than 50 percent results in a smaller reduction of about 0.31 Mg ha^{-1} yr^{-1}. Conversely, the incorporation of cover crops has been reported to increase soil organic carbon by about 0.49 Mg ha^{-1} yr^{-1} (Chahal et al., 2020) [16].

Water management to reduce GHGs emisssion

The System of Rice Intensification (SRI) is promoted as a water-saving rice cultivation method. It is an alternative rice production technique in which young seedlings (10–14 days old) are transplanted at wider spacing (25 cm $\times$ 25 cm), and the soil moisture is maintained close to field capacity rather than under continuous flooding. Rice plants grown under SRI generally develop larger root systems, greater root biomass, and strong, taller tillers with improved photosynthetic capacity.

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The practice of alternate wetting and drying in SRI promotes higher microbial activity compared to the conventional continuously submerged rice cultivation system (Thakur et al., 2017) [17]. Soil microorganisms in the rice rhizosphere play an important role in sequestering atmospheric carbon into microbial biomass. The enhanced root proliferation, increased number of tillers, greater microbial activity, and improved nutrient availability under SRI contribute to a yield increase of about 20–50%. This improvement is largely associated with better root development and increased rhizodeposition in the root zone.

Studies have shown that rhizodeposition of carbon from below-ground plant parts, particularly roots, contributes about 54–63% of the total below-ground carbon input in cereals. Higher biomass production under SRI also results in greater deposition of organic carbon in the root zone. Carbon released by roots is often present in stable forms that contribute to the passive carbon pool, which is important for long-term carbon sequestration.

Moreover, the alternate wetting and drying irrigation regime, along with cono weeding operations, creates favourable aerobic conditions that enhance humification processes. These conditions promote the breakdown of non-humic substances and the formation of humic and fulvic acids more effectively than in conventional submerged rice systems (Thakur et al., 2017) [17]. Thakur et al. (2017) [17] also reported that methane (CH_4) emissions from rice fields were significantly reduced under SRI, with a reduction of about 64.15% compared to conventional rice cultivation Table 3.

Table 3: Emission of CH_4 gas during conventional and SRI method rice cultivation (Thakur et al., 2017) [17]

	Conventional method	**SRI**
Total CH4 flux (g CH_4 / m^2)	31.47	10.09
Reduction in methane emission (%)	-	64.15

Importance of soil conservation in C neutral agriculture

Soil carbon (C) stocks are a crucial component of the global carbon cycle. Historical estimates suggest that soils may have lost up to 27 percent of their original carbon content since the beginning of agriculture nearly 10,000 years ago. Soil erosion and the subsequent redistribution of sediments can significantly disturb soil carbon in both managed and natural landscapes. The ultimate fate of soil carbon affected by erosion varies depending on whether the carbon is lost from the site of erosion, transported during redistribution, or accumulated at deposition sites Figure 7 (Mandal et al., 2020) [2].

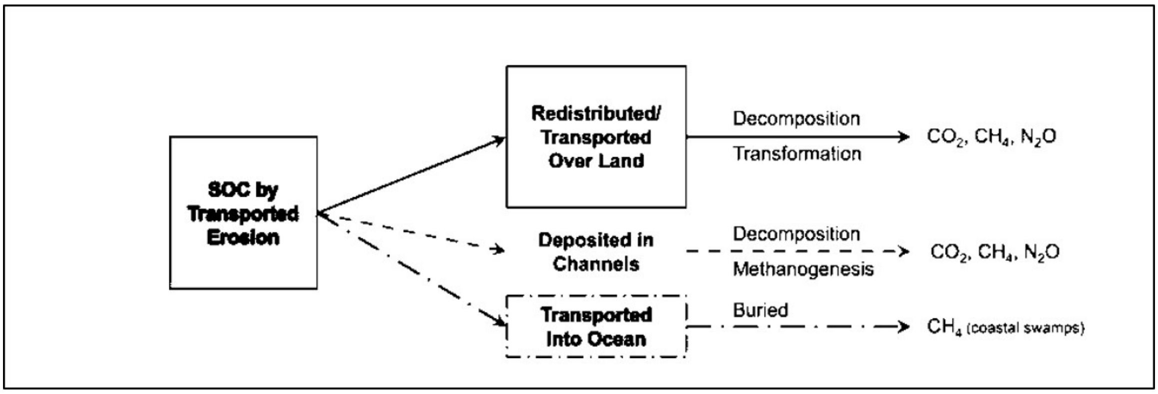

Figure 7: Flow chart showing effect of soil erosion on soil organic carbon (Mandal et al., 2020) [2]

Forests play a vital role in both the mitigation of and adaptation to climate change, as they function as both carbon sinks and carbon sources. According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), activities related to agriculture, forestry, and other land-use changes contribute about 24% of global greenhouse gas (GHG) emissions, while vegetation and soils together account for nearly 30 percent of global carbon sequestration (IPCC, 2019) [18]. Forest vegetation and soils together store approximately 1240 Pg of carbon and possess a high potential for carbon sequestration, estimated at about 0.4 Pg C yr^{-1} in forest soils and 1–3 Pg C yr^{-1} in forest biomes. Currently, forests hold around 39 percent of the total carbon stored in soils worldwide. However, the amount of carbon stored in forest soils varies depending on region and forest type.

Agroforestry

Forests perform a dual function as both sources and sinks of carbon, offering a relatively cost-effective approach to climate change mitigation by capturing carbon from the atmosphere and storing it in plant biomass and soil. In addition, forests provide numerous ecosystem services, including food, timber, fuel, shelter, and income for billions of people. Considering their potential, expanding forest and tree cover through afforestation, reforestation, improved forest management, and sustainable forest product utilization is essential for enhancing livelihoods while reducing the carbon footprint.

Agroforestry systems also contribute significantly to terrestrial carbon storage and provide both adaptation and mitigation benefits in the context of global climate change. Agroforestry practices include alley cropping, home gardens, improved fallows, multipurpose trees on farms and rangelands, agri-silviculture, silvi-pasture, agri-horticulture systems, shaded perennial crop systems, shelterbelts, and windbreaks. Various agroforestry systems have been reported to possess higher soil organic carbon stocks Table 4 (Srinivasarao, 2018) [19]. In addition to carbon sequestration, agroforestry systems offer a wide range of economic, environmental, and socio-economic benefits.

Table 4: Effect of different agroforestry system on soil C storage (Srinivasarao, 2018) [19]

Agroforestry system/species	Age (years)	Soil depth (cm)	Soil C (Mg ha^{-1})
Mixed stands – Eucalyptus + Casuarina	4	0–40	61.9
Mixed stands – Casuarina + Leucaena	4	0–40	56.6
Agrisilviculture	5	0–60	27.4
Silvopastoral system	14	0–100	173.0
Alley cropping	13	0–10	12.6
Agroforest (Home & outfield garden)	13	0–40	45.0

Government initiatives to achieve carbon neutral agriculture

Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)

The major objectives of the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY) include increasing investment in irrigation infrastructure to expand the area under assured irrigation at the field level. The scheme also aims to improve on-farm water use efficiency through better utilization of water resources and reduction of water wastage. It promotes the expansion of precision agriculture and the adoption of advanced and improved irrigation technologies.

In addition, PMKSY encourages the use of water-saving technologies such as drip irrigation under the concept of "More crop per drop." It also focuses on groundwater recharge through various water conservation measures, recharge of tube wells, and the reuse of treated municipal wastewater for peri-urban agriculture. The scheme further promotes private sector participation and investment in precision irrigation systems.

Overall, PMKSY contributes to the conservation of natural resources and brings more land under cultivation through efficient water management. This can enhance vegetation cover, increase biomass production, and improve soil organic carbon (SOC) storage, thereby supporting efforts toward achieving carbon neutrality.

National Food Security Mission (NFSM)

The interventions implemented under the National Food Security Mission (NFSM) include cluster demonstrations on improved packages of practices, demonstrations on different cropping systems, distribution of seeds of high-yielding varieties (HYVs), and the provision of farm machinery and resource conservation tools. The program also promotes the use of efficient water application equipment, plant protection measures, nutrient management practices, and soil ameliorants, along with cropping system–based training programs for farmers. These interventions not only contribute to achieving food security but also help improve soil health and enhance soil organic carbon (SOC) storage.

Paramparagat Krishi Vikas Yojana (PKVY)

The Paramparagat Krishi Vikas Yojana (PKVY) is a sub-component of the Soil Health Management (SHM) scheme under the National Mission for Sustainable Agriculture (NMSA).

The scheme aims to promote sustainable models of organic farming by integrating traditional agricultural knowledge with modern science and technology. Its objectives include conserving natural resources, improving long-term soil fertility, and supporting adaptation to and mitigation of climate change. PKVY primarily focuses on enhancing soil fertility and producing safe and healthy food through organic farming practices without the use of agrochemicals.

Challenges in carbon neutral agriculture

Several barriers to the adoption of carbon farming are directly related to the interests and perspectives of landholders, as well as limitations in skills and management capacity. Political instability can also significantly influence the acceptance and implementation of such practices. In addition, uncertainty regarding environmental impacts, along with limited awareness of relevant schemes and policies, may further hinder their adoption (Sharma et al., 2021) [20].

Other challenges in C neutral agriculture are:

- Lack of technical soundness
- Lack of interest of farmers
- High initial cost
- Longer gestation period for some measures (Agroforestry)
- Risk in preparing carbon budgeting
- High vulnerability to weeds and pest incidence
- Herbicide tolerance of crops

Conclusion

Carbon-neutral agriculture offers a sustainable land-use management approach that benefits both the environment and society. Such systems are highly efficient in maintaining and enhancing soil organic carbon (SOC) stocks. Compared to monocropping systems, carbon-neutral farming systems have a greater capacity to accumulate SOC, thereby improving soil quality and overall soil health. To overcome existing barriers and promote low-carbon options in Indian agriculture, strong policy support, technological innovations, and increased investments are essential. These measures will enable farmers in India to transition towards carbon-neutral agricultural practices.

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