

Strategies for Enhancing Carbon Sequestration in Plants and Soil through Agricultural Activities

SAMAR SINGH, RANJEET SINGH BOCHALYA AND SULTAN SINGH*

Faculty of Agriculture, Maharishi Markandeshwar (Deemed to be University), Mullana Ambala-133 207 (Haryana), India

**(e-mail: sultan.hau@gmail.com; Mobile: 99927 03833)*

(Received: December 4, 2025; Accepted: March 8, 2026)

ABSTRACT

Global agriculture and ecosystems including their capacity to secure food are faced with climate change as a major obstacle. Carbon sequestration in soil and plants has emerged as one important means of reducing CO₂ concentrations in the atmosphere. Approximately 19-25% of greenhouse gasses produced by humans are attributed to the agricultural sector; it has a significant opportunity to become a dominant form of carbon sink material. Total estimated carbon sequestered or deposited in soil has been estimated between 1500-2400 Giga tons almost three times more than what is present in the atmosphere. With a 0.4% annual increase of soil organic carbon as recommended by the 4 per 1000 initiative, a large portion of CO₂ released into the atmosphere can be sequestered. Soil degradation is one of the greatest threats to food security; however, by implementing sustainable farming practices, one can reduce the level of degradation and stabilize soil organic carbon reserves. Sustainable farming practices include planting and protecting tree cover, changing traditional agricultural production and landscapes, planting vegetative materials. This paper provides analysis of the soil and plant strategies available to sequester carbon, including the following agro forestry, conservation agriculture, use of cover crops, diversifying crop species, using biochar and using integrated nutrient management. This paper reviews how policy and economic incentives, as well as emerging digital technologies, affect the functioning of plants in terms of increasing carbon storage through improved efficiency of carbon fixation by photosynthetic means and maintaining appropriate levels of carbon in soils. The functional characteristics of plants, such as increased plant biomass, prolonged leaf life, stay green and roots with high lignin content represent potential pathways for developing new types of crops that will be successful under changing climatic conditions. The use of functional traits to develop crops that are resilient to climatic stresses will enhance not only soil organic matter but will also provide substantial benefits in conserving natural resources, enhancing diversity, improving the health and productivity of soils and crops and improving resiliency to extreme weather events in the ecosystems in which these types of crops grow.

Key words: Carbon sequestration, organic carbon soil, conservation agriculture, biochar

INTRODUCTION

Most people believe that one of the most significant ecological concerns of the 21st century is global climate change. The primary cause of climate change is the rapid increase in the atmospheric concentration of greenhouse gases (GHGs) including carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) caused by soil organic carboniety through activities such as burning fossil fuels for energy, deforestation and intensive farming methods. The fact that the average global temperature has gone up and has caused changes in where rainfalls and that weather events are occurring more often and with greater intensity is impacting how much food is produced, how stable ecosystems are and

the amount of food security (IPCC, 2023). Agriculture is one of the several human activities that contributes to climate change and produces between approximately 19-25% of all the GHGs produced by people in the world, the majority of that is methane which comes from growing rice and raising livestock and nitrous oxide from using nitrogen fertilizers (Smith, 2019). However, although agriculture produces a large amount of GHGs it has the potential for a significant amount of carbon sequestration to help mitigate climate change through plants and soil (Lal, 2020). Soils are an enormous store of organic carbon on land, with soil accounting for approximately 1,500-2,400 giga tonnes of carbon. That is about twice as much carbon as present in the atmosphere and nearly three times as much as is stored

in all live vegetation (FAO, 2022), so soils have a very important role in the global carbon cycle and could potentially provide a means for climate change mitigation. Just a small amount of additional soil organic carbon will have a great effect on reducing the amount of CO₂ in the atmosphere. Increasing soil organic carbon enhances the ability of soils to sequester carbon as well as increases the amount of soil fertility, soil structure, soil water retention, soil nutrient cycling and overall agricultural sustainability (Paustian *et al.*, 2019; Lal, 2020). Carbon sequestration is the long-term storage of carbon dioxide in vegetation, soil or other natural forms, to mitigate or postpone the climate crisis. Most organisms obtain their carbon from vegetation which contains both organic carbon and inorganic carbonate. In agricultural systems, carbon is stored primarily through photosynthesis in which plants capture carbon dioxide from the atmosphere and turn it into organic forms. Eventually, the plant's organic carbon gets deposited in soil through the plant's root system, crop residue and litter fall (Fan *et al.*, 2023). A small proportion of organic carbon is held within mineral-bound and aggregate types and therefore contributes to the long-term soil organic carbon pool. Consequently, soils can act as dynamic carbon reservoirs by releasing or storing carbon based on our management practices and the environmental parameters surrounding agricultural soils.

Initiatives to boost soil carbon storage are part of a global effort, including the "4 per 1000" (4%) programme that was proposed at the 2015 Paris Climate Conference. This initiative is based on the idea that if we increase global stocks of soil organic carbon by 0.4% each year, it will compensate for a significant proportion of the world's annual GHG emissions (Minasny *et al.*, 2017). In India, where agriculture supports almost 50% of the population, using soil as a carbon sink offers the dual advantage of lessening the impact of climate change and improving people's livelihoods. In addition to helping farmers increase their soil organic carbon levels by using management practices that lead to sustainable farming, these practices enhance soil resilience, increase crop yields and improve water-use efficiency, thus promoting

food security in regions that are susceptible to climate change (Singh *et al.*, 2020). As well as reducing global warming, carbon sequestration through agriculture offers numerous co-benefits. A number of agronomic and ecological practices have been identified that can enhance carbon sequestration in agricultural communities. Carbon-enriched soils are generally more productive and have better structures with greater resilience to drought and flooding. Higher organic matter content also enhances cation exchange capacity, nutrient availability and levels of biological activity, thus enabling sustainable yields from crops over time. Particularly, the discussed approaches have aligned with the principles of climate-smart agriculture that seek to integrate productivity, adaptation and mitigation goals (FAO, 2022).

Achieving significant soil carbon sequestration is not without its challenges, as soil organic carbon accumulation is a slow process and requires a number of years or decades before noticeable results can be seen. Moreover, the ability to measure changes in soil organic carbon accurately is complex due to fluctuations in spatial variability and limitations of measurement methodology. Accessibility to finance as well as low levels of awareness amongst farmers is barriers to implement sustainable soil carbon practices. The successful removal of these barriers will require a comprehensive policy framework, financial incentives, carbon credit systems and capacity-building programs. Initiatives such as India's national mission for sustainable agriculture and the global 4 per 1000 initiative can be leveraged to develop and promote carbon-aware farming practices (IPCC, 2023). While the agricultural industry is responsible for a significant portion of the world's greenhouse gasses emissions, it also has the capability to become a net carbon sink through improved practices and management of land. Countries can achieve several environmental goals, including the reduction of carbon emissions, improvements to their soils and increased food supply, by concentrating their efforts to sequester CO₂ through soils and plants. In order to achieve sustainable soil organic carbon sequestration, it is critical to combine scientific innovation with farmer involvement and agricultural policy support.

PLANT-BASED STRATEGIES FOR CARBON SEQUESTRATION

The plant based carbon capture and storage is a method of capturing and storing carbon dioxide (CO₂) from the atmosphere by enhancing natural processes. Plant-based carbon capture and storage is essential in mitigating climate change, enhancing soil health and developing sustainable agricultural practices.

AGRO-FORESTRY SYSTEMS

Agro-forestry, the practice of integrating trees with crops or livestock, serves as an effective strategy for carbon sequestration. Trees capture CO₂ through photosynthesis and store carbon in their biomass and roots, while simultaneously improving microclimate, reducing soil erosion and enhancing biodiversity. Agro forestry systems significantly increase both above and below-ground carbon storage and deliver additional ecosystem services. Studies from India indicate that poplar and eucalyptus based systems can sequester between 4 and 9 Mg C/ha/yr (Dhyani *et al.*, 2019), while other studies report sequestration rates of 2 to 9 t CO₂/ha/yr depending on tree species, age and density (Nair *et al.*, 2019). Root turnover and litter deposition further contribute to long-term soil organic carbon accumulation (Table 1). Conversion of forest land to non-forest uses often results in the permanent loss of all or a substantial part of biomass carbon and a decline in soil organic matter. Although some carbon may be retained in wood products when harvested biomass is utilized, substantial emission of CO₂ and other GHGs occur when the remaining biomass and organic matter is burned or decomposed. Maximizing carbon sequestration in forests and wood products requires an integrated understanding of forest ecosystem dynamics and sustainable utilization practices.

Cover Crops and Green Manures

Cover crops are important in conserving soil as they help in reducing soil erosion, increasing the organic matter and increasing the activity of the soil's microbes. They also help sequester carbon from the atmosphere, as they improve soil structure and provide organic matter to the soil. Other practices that help build soil carbon include cover cropping, green manuring and utilizing efficient nutrient and water management techniques for building soil organic carbon while diminishing carbon losses associated with erosion. Legume species are able to enhance soil fertility via biological nitrogen fixation and under these practices, soil organic carbon gain has been documented to be 0.3-1.5 t/ha/yr in temperate and semi-arid climates. Incorporating green manures increases the carbon input to the soil, which fosters the formation of humus (Table 1). Cover crops offer a number of methods for protecting both soil and soil organic carbon, their canopy absorbs the impact of raindrops and thus protects against erosion, while their roots hold the aggregates in place and when they decompose, they contribute organic matter and carbon back to the soil (Yang *et al.*, 2021). The formation of humic substances is aided through this process, which subsequently contributes to the creation of microbial biomass and ultimately increases the carbon pool found in soil. Leguminous cover crops such as clovers (*Trifolium* spp.) and vetches (*Vicia* spp.), are some of the more common examples of leguminous cover crops and provide nitrogen-fixing capabilities that provide additional fertility to the soil. Cover crops that are not legumes, like oats (*Avena sativa*) and rye (*Secale cereale*) grow very fast and produce a lot of biomasses for soil cover. Some brassicas, like mustards (*Brassica* spp.) and radishes (*Raphanus sativus*), have a unique characteristic where they can grow very deep

Table 1. Carbon sequestration potential of different agro forestry systems

Agro-forestry type	Soil organic carbon increase (t C/ha/yr)	Above ground biomass C (t C/ha/yr)	Reference
Alley cropping	0.5-1.2	2-4	Nair <i>et al.</i> , 2019
Silvopasture	0.7-1.5	3-5	Nair <i>et al.</i> , 2019
Home gardens	0.3-0.8	1-3	LaI, 2020
Wind breaks	0.2-0.5	0.5-2	FAO, 2022

into the soil, improving soil structure, resulting in alleviation of compacted soils (Bodner *et al.*, 2021).

Crop Diversification and High-Biomass Varieties

Using high-biomass crops and crop rotations help promote the movement of carbon into the ground and help develop organic carbon in the soil. The use of legumes, oils and millets will allow for greater carbon cycling and support a greater diversity of soil microbes. Deep-rooted plants can also hold carbon reserves below the surface soil. The system, when designed correctly, can create two different rooting patterns, which will impact nutrient movement, water movements and the ability of the soil to store carbon long-term. Intercropping or relaying crop systems allow for additional constant carbon being added back into the soil, which will continue to create healthier soil for the future. Crop rotation is the same as growing multiple crops on the same fields, it also helps maintain soil fertility and disrupts pest and disease cycles by varying nutrient uses and root depths. Crop rotations can help with a greater breakdown of organic matter into more stable carbon in the crop rotation process. Legumes have been shown to fix nitrogen from the atmosphere and add to soil fertility, ultimately allowing for a greater biomass production, increasing the volume of residue returned to the soil and therefore increasing the carbon storage ability of the crop rotation (Kumar *et al.*, 2018). Liu *et al.* (2022) demonstrate that diversified crop rotations can increase soil organic carbon by up to 8.5% over 12 years compared to monoculture system, primarily due to greater residue inputs and varied root structures that improve microbial activity and soil aggregate stability (Fig. 1).

Biochar Based Seed Coating as a Plant Centric Strategy for Carbon Sequestration

Biochar is the super stable organic matter packed with carbon, produced by heating plant material in the absence of oxygen. Due to the significant variability in the feed stocks used for production and the conditions of pyrolysis, biochar may exhibit a wide range of physical and chemical characteristics. The primary

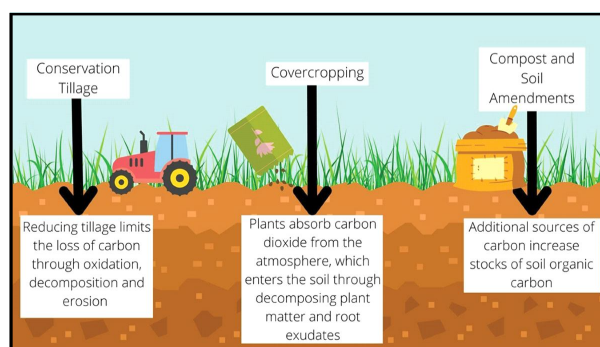


Fig. 1. Management strategies to enhance agroecosystem's soil carbon sequestration.

chemical discrepancy between biochar and other organic materials is the significantly greater amount of reduced aromatic structures and aromatic carbon, which is the main factor behind biochar's high stability. In case of the elements in biochar, the organic components primarily consist of carbon, while the inorganic part may include various micro and macro elements like inorganic carbonates, sodium, potassium, magnesium, calcium, zinc, copper, iron and others. Biochar is typically defined by its extensive specific surface area, porous framework, high cation exchange capacity, and surface functional groups, all of which are directly related to its adsorption capabilities. According to a recent study, rice emergence and seedling stand were significantly improved by seed coating with an appropriate ratio of biochar (Zhang *et al.*, 2023). The improvement of the availability of water and rich nutrients surrounding the seed, which is brought about by biochar functioning i.e. porous structure may be the cause of this promotion in stand establishment (Fig. 2). According to Elamparithi *et al.* (2021) brinjal seeds coated with biochar and organic materials showed greater germination and seedling development than uncoated seeds. In a similar vein, Parvin Banu *et al.* (2022) discovered that, when compared to untreated black gram seeds, seed coating with biochar (200 g/kg of seed) showed the highest germination rate, shoot length and root length. Biochar seed coating enhances carbon sequestration due to the addition of highly inert, aromatic based carbon in soil through a chemical process (carbonization) in producing biochar, making it resistant to the breakdown. Biochar provides a porous framework and high cation exchange capacity

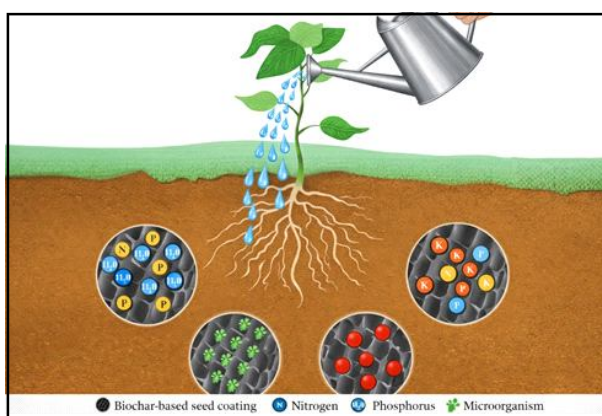


Fig. 2. Synergistic mechanisms of biochar-based seed coatings in enhancing plant growth. that create a nutrient rich microenvironment around seeds. Therefore, an increase in seed germination and biomass leads to a higher volume of atmospheric carbon dioxide being absorbed via photosynthesis. Moreover, biochar is able to absorb a large number of organic materials and anionic carbonates within a soil matrix, providing a long-term means of storing carbon.

PLANT CHARACTERS CONTRIBUTING TO CARBON SEQUESTRATION

The characteristics of a plant are a key factor comparing how well or efficiently plants will sequester carbon from the atmosphere within an agricultural environment. Plant characteristics such as high biomass production, optimized canopy architecture, extended leaf area duration and the presence of stay-green characteristics enable a greater cumulative amount of photosynthetic carbon to be captured. Also, below-ground plant characteristics such as deep and extensive rooting systems, high root turnover rates and high levels of lignin within a plant's tissue allow for continued long-term carbon storage within soils through increased persistence of soil organic carbon. Continuous carbon fixation is achieved by integrating perennial growth habits with strong regrowth capabilities and reducing soil disturbances and potential carbon losses (Panchal *et al.*, 2022). Intrinsically, incorporating functional traits of plants into crop improvement programs provides an opportunity for sustainable plant-based carbon sequestration while simultaneously increasing crop productivity and climate resiliency.

Biomass Produce and Harvest Index Trade Offs

Biomass production is the main factor of how much CO₂ is sequestered in the atmosphere through plant-based mechanisms, as the carbon captured during photosynthesis is directly influenced by how much dry matter is produced by the plant. Generally, more biomass produced means greater amounts of CO₂ will be sequestered (absorbed) by the plant both above and below ground. In agricultural systems, however, plant breeding has tended to favour high harvest index (HI), which is defined as the amount of economic yield produced as a percentage of total plant biomass, this trend has often come at the expense of producing total vegetative growth, which has increased the efficiency of yields, but may have decreased modern cultivar's ability to carbon sequestration. With the removal or rapid decomposition of crop residues, these breeding selection processes may have further impacted carbon sequestration potential (Lorenz and Lal, 2018).

The balance between biomass production and the harvest index is key to improving crops in ways that minimize their carbon footprint. Crops bred for high harvest indexes place more of the carbon they absorb into their grain or seeds, whereas crops bred for lower harvest indexes often retain more of the carbon in their stems, leaves and roots, thereby contributing to the soil's organic carbon reserve through the incorporation of plant residues after harvest (Camargo-Alvarez *et al.* 2023). Programs of breeding that focus on optimizing harvest index rather than maximizing harvest index will provide a greater opportunity to enhance sustainable, climate-resilient agricultural systems compared to those focused only on maximizing production. In addition to creating dual-purpose ideotypes that can produce both competitive yield and improve total biomass production, it is important to effectively manage agronomic systems to optimize the potential benefit of these systems. Management practices such as the retention of crop residues, reduced tillage and utilizing crop rotation systems will help maximize the benefit derived from retaining the soil's organic carbon associated with fast-growing, biomass-rich cultivars. Ultimately, future breeding strategies are

likely to focus specifically on the creation of carbon efficient harvest indices as a combination of a high level of productivity and the provision of ecosystem services, indicating a shift away from breeding lines entirely focused on yield to developing more multifunctional crop plant improvements (Razzaq *et al.*, 2021).

Leaf Area Duration, Canopy Architecture and Carbon Assimilation

Leaf area duration (LAD) is the amount of time that a leaf canopy is photosynthetically active and functioning. This factor has a major impact on total carbon assimilation for the entire growing season. Leaf area index (LAI) indicates the current size of the leaf canopy, while LAD brings together the size (magnitude) and time period of time (length) that the leaf canopy was photosynthetically active. Thus, LAD is a better indicator of how much carbon can be captured over a season compared to LAI alone. In particular, when LAD is extended, the crop can continue to assimilate additional carbon as it matures during later growth stages and when the possibility of delaying senescence is created due to optimal or stressful conditions (Kuai *et al.*, 2022). Canopy architecture also affects the influences photosynthesis efficiency or how much or what kind of light gets intercepted and scattered in the canopy, by enhancing the quality of light intercepted, optimizing leaf angle, and balancing layering between leaves in the canopy so that they are not shaded out (self-shading). With improved canopy structure, it becomes possible for deeper penetration into the canopy for the purpose of photosynthetic activity (more leaf area, greater photosynthesis) thereby increasing the overall carbon assimilation (total per-acre) without increasing the number of inputs required (Burgess *et al.*, 2017). Leaf area duration and canopy architecture characters can be genetically selected for through each respective breeding methods and are highly heritable. As technology advances, greater precision in measuring both canopy dynamics (by UAV based imagery) and photosynthetic persistence will become increasingly possible. In addition, the contribution of uniform stands to rapid canopy closure and the capture of carbon during early establishment must be taken into account

when selecting for seed vigour traits. With a greater frequency of climate change due to increased temperatures, drought and low nutrient content, genotypes that can withstand these conditions while maintaining LAD will be highly preferred (Li *et al.*, 2022). By continuing to assimilate carbon at a low level when conditions are not optimal for growth (e.g., a heat wave) the carbon assimilation energy stabilized via these plants through maintaining their canopies will increase the ability to produce a stable cereal grain crop or other crops and increase the carbon sequestration within the agro-ecosystem (Firn *et al.*, 2019).

Stay Green Traits and Extended Carbon Fixation

The trait of stay green is defined as the slowing of leaf senescence and delaying in its initial occurrence. The presence of this trait allows more time for the plant to produce carbohydrates, which is particularly important for carbon assimilation under abiotic stress such as heat, drought and nutrient deficiencies. Genotypes that exhibit functional stay green retain chlorophyll, membranes and other photosynthetic enzymes that allow for continued CO₂ fixation after the end of a normal grain-filling stage. Galyuon *et al.* (2019) showed that the stay green mechanism led to less breakdown of the photosynthetic apparatus, as well as improved nitrogen metabolism and continued turnover of chlorophyll and supported a higher quantity of active enzymes that play an integral role in photosynthesis. In terms of the potential for increased carbon sequestration due to extended rates of photosynthesis, more cumulative CO₂ capture has occurred and therefore, more biomass accumulation due to the extended periods of photosynthesis (Ma *et al.*, 2023). In addition, stay greens typically allocate more carbon to their stems and roots than their upper portions. This type of plant provides the potential for a larger carbon deposit from the upper portion of the roots to support soil carbon stabilization since the carbon found in roots persists longer than that found in shoots. Stay-green is a genetically complex trait with many pathways involved, including hormonal regulation (ethylene and cytokinins), nitrogen remobilization efficiency

and antioxidant capacity. From a breeding perspective, stay green traits have been successfully incorporated into crops such as sorghum, maize, wheat and millets, primarily for yield stability (Ma *et al.*, 2024). However, their role in climate mitigation has recently come into focus. However, it is important to note that all stay-green phenotypes are equal, as cosmetic stay- green types may retain chlorophyll but lack photosynthetic efficiency. Because of this, functional validation is critical. Integrated stay-green traits with seed-based stress resilience and optimal canopy traits can further enhance the roles of stay-green traits in carbon sequestration. As such, future climate-smart breeding programs should make stay-green traits a strategic target (Dwivedi *et al.*, 2018).

Lignin Content and Recalcitrant Biomass in Carbon Storage

Lignin is an intricately structured phenolic polymer that adds to rigidity and resistance to decay in the cell walls of plants. The presence of lignin greatly impacts how stable or persistent carbon from plants remains in soils. In general, the greater the amount of lignin contained within biomass, the longer the time frame between decay and carbon returning to soils (Li and Tasnady, 2023). Therefore, the presence of lignin within organic matter will have a greater role in long term carbon storage and sequestration in conservation agriculture. From a biochemical perspective, lignin is difficult for microorganisms to break down and therefore adds a lower rate of carbon mineralization (Ma *et al.*, 2018). More often than not, root tissue is composed of higher levels of lignin compared to shoot tissue. In addition, as root tissue contributes significantly towards creating stable fractions of carbon within soils, if bred plants for increased below ground deposition of lignin, one would have a large opportunity to increase soil carbon storage without necessarily increasing the total amount of above ground biomass. The presence of lignin provides both pros and cons in relation to forage quality and digestibility, as well as processing efficiency of biofuel crops (Ghosh *et al.*, 2018). Therefore, the optimization of lignin levels will be determined based on the intended use for each type of crop. The current methods of molecular

breeding and biotechnological advances provide a means of targeting the alteration of the lignin chemical makeup instead of simply lowering the overall amount of lignin present leading to increased carbon storage with reduced adverse agronomic impact. In terms of seeds, if look at the development and advancement of crops, it is becoming increasingly clear that in order to master how the lignin synthesis pathway operates and the different environmental conditions affecting this synthesis pathway are critical (Sattlewal *et al.*, 2018). Ultimately manipulating lignin characteristics and managing crop residue can create a dramatic increase in the ability of agricultural land to store carbon. The development of sustainable agricultural methods through the introduction of plant functional traits into crop breeding programs will allow for increased productivity with enhanced climate mitigation potential in agro-ecological systems (Fig. 3).

SOIL-BASED STRATEGIES FOR CARBON SEQUESTRATION

Carbon sequestration refers to the long term retention of carbon within oceans, soils, vegetation and geological formations. While oceans store the largest carbon reservoir on earth, soils account for approximately 75% of the carbon pool on land nearly three times more than the amount stored in living plants and animals. Therefore, soil plays a critical role in regulating the global carbon cycle and maintaining its equilibrium.

Soils are the largest terrestrial reservoir of organic carbon and hold major potential for climate change mitigation through management practices that increase soil organic carbon stocks and stabilize organic matter (Lal, 2020; FAO, 2022). Living soil fauna and flora decomposed organic materials and their byproducts known as humus comprise soil organic matter and are involved in converting atmospheric carbon to stable soil carbon pools. Soil based strategies to capture carbon in the soil environment focus on increasing the amount of carbon in the soil, which will result from incorporating more plant residues and root biomass into the soils, adding organic-material amendments, decreasing the loss of carbon by increasing consideration of the oxidation, erosion and

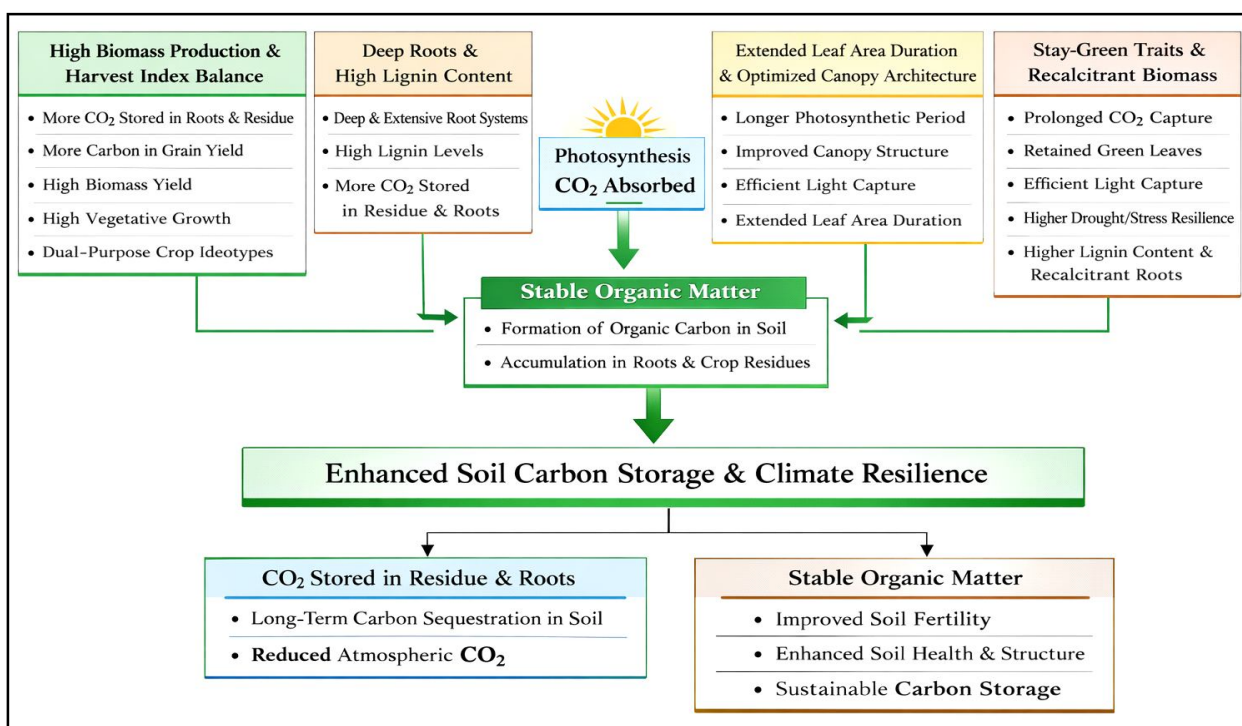


Fig. 3. Plant functional traits driving long term carbon sequestration in agro-ecosystems.

mineralization of carbon and increasing the ability to store carbon via treatment with recalcitrant materials or stabilization techniques. Soil capture of carbon can be accomplished through a variety of land management systems that bolster soil health while also playing a role in organic and regenerative agriculture. Accordingly, the following section precisely describes the most effective, scalable soil capture strategies and the methods of implementation, as well as related issues (Table 1).

Conservation Agriculture

Conservation agriculture is based on three main principles, minimal disturbance of the soil, retention of crop residue and crop rotation (Jat *et al.*, 2019). Reduced tillage associated with conservation agriculture decreases the amount of organic matter oxidized in the soil and as a result, the annual increase in soil organic carbon is between 0.1 and 0.3 t C/ha (Lal, 2020). By retaining the crop residue on the soil surface, the continuous carbon input is provided to the soil, allows for better soil organic carbon aggregation and improves soil structure (Table 2). However, it has been reported that conservation agriculture with minimal disturbance of the soil, retention of

crop residues and crop diversification has increased soil organic carbon by 0.1 to 0.3 tonnes C/ha annually when compared to conventional tillage (Zomer *et al.*, 2016). Multiple published studies have reported that the conservation agriculture practice supports improvement of the physical, chemical and enzymatic properties of the soil when compared with a conventional tillage practice. Besides this, conservation tillage decreases the amount of fossil fuel used during field operations which further increases its potential support for sustainable agriculture.

Biochar Application

Biochar is made through pyrolysis i.e. the heating of organic materials without oxygen, from things such as crop residue and animal waste. Its high carbon content makes it a good way to store carbon dioxide (CO₂). One metric tonne of biochar is equivalent to three metric tonnes of CO₂, however, biochar stays in the soil for decades to many centuries and retains carbon until it is naturally released back into the atmosphere through microorganisms and weathering effects. In addition to enhancing soil fertility, improving water retention, aeration, nutrient holding capability and reducing bulk density and soil erosion, it offers

Table 2. Comparison of different sowing methods for carbon sequestration and soil health

Sowing methods	Description	Soil organic carbon impact (t C/ha/yr)	Biomass C (t/ha/yr)	Yield effect	Soil health impact	Reference
Broadcasting	Seeds scattered manually or mechanically	Low (0.05-0.1)	Low (1-2)	Moderate	Minimal soil disturbance	Lal, 2020
Line sowing	Seeds sown in straight rows	Moderate (0.1-0.2)	Moderate (2-3)	High	Better root development	ICAR, 2021
Drill sowing	Mechanized sowing with seed drill	Moderate (0.15-0.25)	Moderate (2-3.5)	High	Uniform spacing, less compaction	Nair et al., 2019
Ridge and furrow	Seeds sown on ridges, furrows for drainage	Moderate (0.1-0.2)	Moderate (2-3)	High	Improved drainage, reduced erosion	FAO, 2022
Zero tillage	Seeds sown without plowing	High (0.2-0.4)	Moderate (2-3)	High	Preserves soil organic carbon, reduces erosion	Lal, 2020
Minimum tillage	Reduced plowing and soil disturbance	Moderate (0.15-0.3)	Moderate (2-3)	High	Preserves soil structure	Singh et al., 2020
Bed planting	Seeds sown on raised beds	Moderate (0.15-0.25)	Moderate (2-3)	High	Good aeration, reduces waterlogging	ICAR, 2021
Transplanting (rice)	Seedlings grown separately and transplanted	Moderate (0.1-0.2)	Moderate (2-3)	High	Reduces weed pressure	Nair et al., 2019
Precision sowing	Seeds sown at exact spacing with machinery	High (0.2-0.35)	Moderate-High (2.5-4)	Very High	Efficient nutrient use, less compaction	FAO, 2022
Hydroponic/direct seeding	Seeds sown in water-based system (paddy)	Moderate (0.1-0.2)	Moderate (2-3)	High	Maintains soil carbon indirectly	Lal, 2020

enhanced potential for nutrient retention through the availability of positively charged ions. Biochar also raises the pH of the soil, making it more alkaline, which allows beneficial soil microorganisms to flourish (Guo, 2020). Furthermore, due to its multi-cavity structure, it has the ability to store beneficial microorganisms in the soil, aiding the enzymatic breakdown of organic matter and nutrient cycling (Pahari *et al.*, 2025). In combination with conservation agriculture, biochar also enhances soil structure and helps conserve moisture in the soil and increase crop yields while reducing greenhouse gases (Ullah *et al.*, 2024). In many ways, therefore, biochar is an ideal multi-purpose agricultural amendment for both the sustainable conservation of soil and water resources and long term carbon stabilization in soils (Table 3).

Organic Amendments and Integrated Nutrient Management

The use of organic amendments such as farmyard manure, composts, green manures and crop residues helps to maintain the level of soil organic carbon and stimulates the growth of beneficial soil microbes by providing a source of bound and soluble organic carbon as well as many nutrients. Organic amendments can also improve the physical structure, the chemical water-holding capacity and cation exchange capacity and the biological properties of soil. The decomposition of organic matter releases a large amount of soluble organic carbon from the breakdown of organic matter into the soil, which can be used by soil microorganisms in the formation of soil aggregates and their stabilization due to the production of microbial extracellular polysaccharides. The synergies between organic and inorganic fertilizer provide for better nutrient use efficiency and less nutrient loss through leaching or volatilization than a

strategy based on the exclusive use of chemical fertilizers. Long term experiments in different agro-ecological zones report approximately a 0.2 to 0.5% annual increase in soil organic carbon under integrated nutrient management compared to conventional chemical fertilizer strategies. The application of integrated nutrient management is, therefore, an excellent method of achieving a sustainable approach to maintain productivity and soil quality against degradation caused by soil erosion and depletion, to improve carbon sequestration and contribute to nutrient recycling in agricultural systems.

Soil and Water Conservation Practices

Various practices for conserving soil and water, such as contour bunds, terracing and mulching, are critical to reduce soil erosion and to conserve soil organic carbon. Both contour bunds and terraces intercept and redirect water flow, therefore, they will both reduce runoff and loss of soil through minimizing the amount of water moving across the land when these types of structures are in place. Additionally, these methods aid in the enhancement of the infiltration of water and retention of soil moisture (Liao *et al.*, 2021). Both contour bunding and terracing prevent the loss of nutrients to the environment and contribute to the production of greater biomass and accumulation of organic materials within the soils. Mulching of soils by adding either crop residue or organic materials to the surface of soils protects the soil from the erosive action of rainfall, conserves moisture and provides an environment that supports beneficial microbial activity, which helps stabilize organic carbon. Improved irrigation management will have the additional effect of increasing the amount of water that is available to the plants, which will in turn aid in increasing the amount of photosynthesis that can be carried out by the plants, develop

Table 3. Soil-based carbon sequestration practices

Practices	Soil organic carbon increase (t C/ha/yr)	Notes/benefits	Reference
Conservation tillage	0.1-0.3	Reduces soil disturbance	LaI, 2020
Cover crops/green manures	0.3-1.5	Enhances microbial biomass	Blanco-Canqui <i>et al.</i> , 2015
Biochar application	1-3	Long term stable carbon	Fan <i>et al.</i> , 2023
Compost/farmyard manure	0.2-0.5	Improves nutrient cycling	Singh <i>et al.</i> , 2020

larger root systems and therefore allocate a greater amount of biomass to the top and bottom of the plant, all of which indirectly contribute to the ability of plants to sequester carbon in plant-soil systems (Gupta *et al.*, 2019).

FACTORS AFFECTING CARBON SEQUESTRATION IN SOIL

There are various factors both biophysical and management that affect soil's capacity to store carbon. Climate plays an important role in both how much biomass is produced and how quickly organic matter decomposes. Microbial activity and organic matter decomposition occur faster in warm and humid conditions, while cooler and drier conditions reduce these rates, thus favouring greater carbon accumulation in soils. In addition to weather, the soil texture and structure also dictate the carbon retention capability of the soil. For example, soils that allow finer textures (clay and silt) produce

stable organo-mineral complexes which will physically protect organic matter from decomposition by microbes, leading to greater carbon stabilization in the soil when compared to sandy soils. The way in which land is managed and the type of soil has an effect on carbon dynamics. Forest and grassland soils generally have more organic carbon because of the continual deposition of litter and less disturbance, whereas converting them to cropland or degraded land usually leads to significant carbon losses from oxidation and erosion. Changes to land use that typically decrease soil organic carbon stores are deforestation, overgrazing and high-intensity crop production as these practices impede soil structure. On the other hand, sustainable land management practices, such as, conservation tillage, retaining crop residues agro-forestry cover cropping and adding organic amendments all improve vegetative growth, enhance soil productivity and reduce soil erosion, which promotes long-term carbon sequestration (Fig. 4).

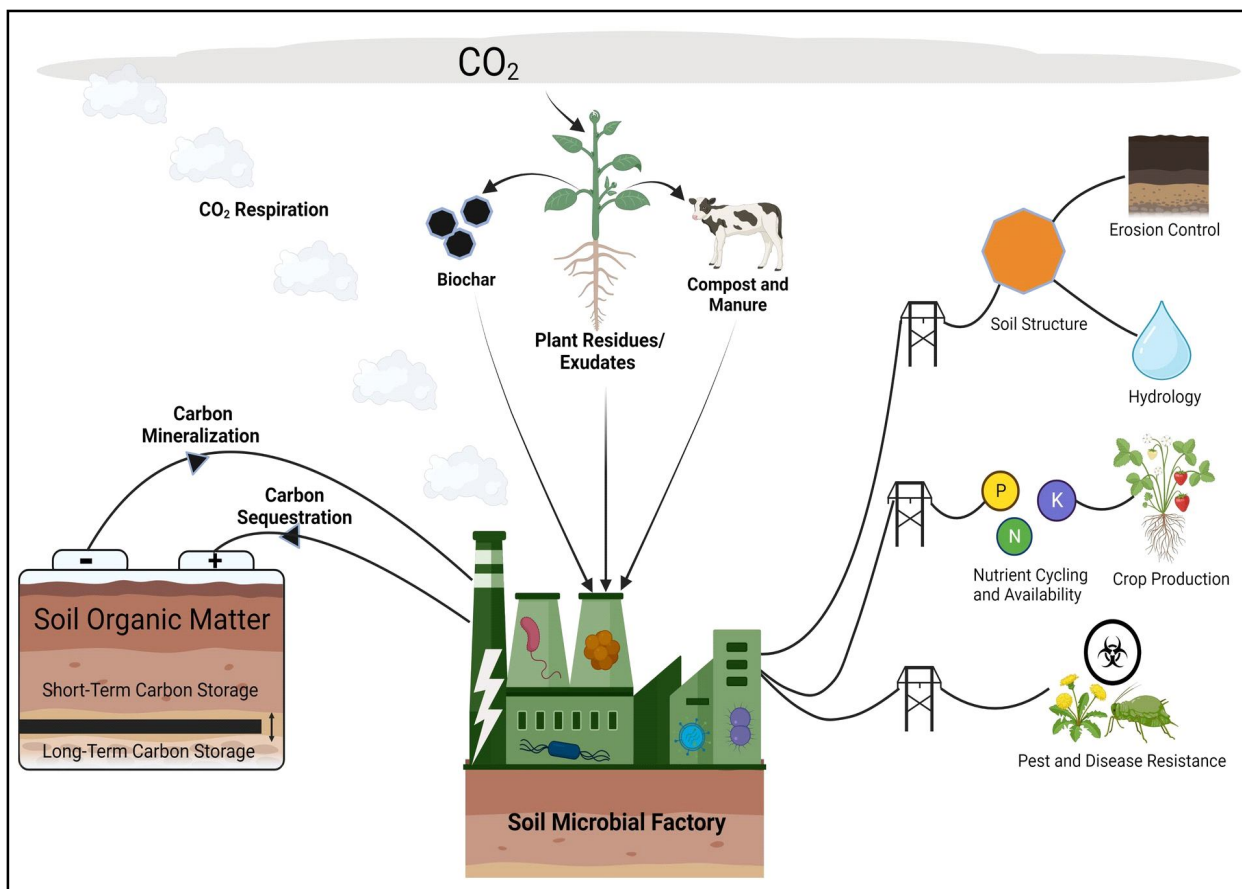


Fig. 4. Interactions between soil, plants and microbes in carbon sequestration and ecosystem functions.

POLICY, ECONOMIC AND TECHNOLOGICAL PERSPECTIVES

Carbon sequestration practices are heavily impacted by policy based incentives. The use of mechanisms such as carbon farming, the carbon credit system and government backed initiatives like the National Mission for Sustainable Agriculture (NMSA) and the Soil Health Card scheme help support sustainable land management practices and increase the desire to adopt them. The worldwide carbon market is expected to exceed US\$100 billion by 2030, showing the increasing economic opportunity associated with carbon trading and efforts to mitigate climate change (World Bank, 2023).

Policy and economics incentives play an important role in the success of sustainable soil management. India has introduced many initiatives that support practices that improve soil health and promote carbon sequestration. For example, the National Mission for Sustainable Agriculture emphasizes sustainable agriculture and soil conservation techniques as part of the National Action Plan on Climate Change (NAPCC) (Prasad and Sud, 2019). This includes the Soil Health Card scheme, which assists farmers in assessing soil quality and providing them with tailored recommendations on how to improve their soils (Reddy, 2018).

Also, the Paramparagat Krishi Vikas Yojana (PKVY) promotes organic agriculture by encouraging the use of compost, promoting a decrease in dependence on chemical inputs, promoting increases in soil organic matter from composted sources and contributing to the storage of carbon. With digital technologies such as remote sensing and GIS platforms now available for accurate measurement of both soil organic carbon change as well as carbon sequestration related to crops, integration of these technologies into national carbon accounting frameworks provides transparency, facilitates engagement in carbon credits and enhances carbon reporting system strength.

CO-BENEFITS, CHALLENGES AND FUTURE DIRECTIONS

The practice of carbon sequestering can generate other benefits, such as increasing soil fertility, retaining more water in the soil,

improving the variety of plants and increasing productivity. Some barriers to adopting carbon-sequestering practices are little awareness of it among farmers, the high cost of implementation, no standard for measuring the benefit and uncertainty in the ownership of the land it is being practiced on. Future research into this will focus on:

- Establish quantification of regional carbon sequestration potential by measuring the abilities of different agro-ecological zones to develop baseline and mitigation strategies within those specific regions.
- Create an economic and efficient way to monitor and verify the sequestration of carbon across all regions through the development of advance digital monitoring and remote sensing technologies.
- Create financial mechanisms for linking farmers and landowners to market for carbon, while maximizing opportunity for equitable participation and improvement in the financial viability of connected value chains.
- Combine traditional or indigenous practices with new technologies in precision agriculture and artificial intelligence to develop the most effective carbon management practices.

CONCLUSION

Increasing carbon storage in agriculture is important for addressing climate change and producing food in a sustainable way. Storing carbon in the soil is an inexpensive and natural method that could help mitigate the effects of climate change on agriculture and has lots of potential to do so. Some integrated practices include, grassed waterway or stream banks, managing fertilizer use, conserving soils through crop rotations, developing bio-fertilizers or composted manures, using grasses, trees, cover crops and weeds for suppressing damaging insects, using alternative sources of energy for farming. Properly implementing these integrated agricultural practices will create significant increases in the amount of carbon in both soil organic matter and stored plant biomass. However, in order for these practices to be

widely adapted, there must be supportive policies, good market incentives and reliable technology for monitoring and verifying the results. Inclusion of plants that store carbon more effectively when breeding crops will allow for higher crop yields and long-term storage of carbon in soils. As climate-smart agriculture continues into the future, the best management practices to optimize the allocation of biomass, maintaining canopy function over time and producing carbon-rich materials in soils will be the focus. The combined efforts of these strategies result in carbon neutrality improve soil health and create more resilient ecosystems, making them an integral part of developing sustainable agricultural systems.

REFERENCES

- Blanco-Canqui, H., Shaver, T. M., Lindquist, J. L., Shapiro, C. A., Elmore, R. W., Francis, C. A. and Hergert, G. W. (2015). Cover crops and ecosystem services: Insights from studies in temperate soils. *Agron. J.* **107**: 2449-2474.
- Bodner, G., Mentler, A. and Keiblinger, K. (2021). Plant roots for sustainable soil structure management in cropping systems. In: *Root Systems in Sustainable Agricultural Intensification*. pp. 45-90.
- Burgess, A. J., Retkute, R., Herman, T. and Murchie, E. H. (2017). Exploring relationships between canopy architecture, light distribution and photosynthesis in contrasting rice genotypes using 3D canopy reconstruction. *Front. Plant Sci.* **8**: 734. doi:10.3389/fpls.2017.00734.
- Camargo-Alvarez, H., Elliott, R. J., Olin, S., Wang, X., Wang, C., Ray, D. K. and Pugh, T. A. (2023). Modelling crop yield and harvest index: The role of carbon assimilation and allocation parameters. *Model. Earth Syst. Environ.* **9**: 2617-2635.
- Dhyani, S. K., Handa, A. K. and Uma, N. (2019). Carbon sequestration and mitigation potential of agro-forestry systems in India. *J. For. Res.* **30**: 1-19.
- Dwivedi, S. L., Siddique, K. H., Farooq, M., Thornton, P. K. and Ortiz, R. (2018). Using biotechnology-led approaches to uplift cereal and food legume yields in dryland environments. *Front. Plant Sci.* **9**: 1249. doi:10.3389/fpls.2018.01249.
- Elamparithi, R., Sujatha, K., Menaka, C. and Senthil, K. (2021). Impact of organic seaweed pelleting on seed quality and biochemical parameters in brinjal seeds. *Pharma Innov.* **10**: 1466-1469.
- Fan, X., Bai, E., Zhang, J., Wang, X., Yuan, W. and Piao, S. (2023). The carbon transfer from plant to soil is more efficient in less productive ecosystems. *Glob. Biogeochem. Cycles* **37**: e2023GB007727.
- FAO. (2022). Soil organic carbon: The hidden potential. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Firn, J., McGree, J. M., Harvey, E., Flores-Moreno, H., Schütz, M., Buckley, Y. M. and Risch, A. C. (2019). Leaf nutrients, not specific leaf area, are consistent indicators of elevated nutrient inputs. *Nat. Ecol. Evol.* **3**: 400-406.
- Galyuon, I. K. A., Gay, A., Borrell, A. K. and Howarth, C. J. (2019). Physiological and biochemical basis for stay-green trait in sorghum. *Afr. Crop Sci. J.* **27**: 653-677.
- Ghosh, A., Bhattacharyya, R., Meena, M. C., Dwivedi, B. S., Singh, G., Agnihotri, R. and Sharma, C. (2018). Long-term fertilization effects on soil organic carbon sequestration in an Inceptisol. *Soil Tillage Res.* **177**: 134-144.
- Guo, M. (2020). The 3R principles for applying biochar to improve soil health. *Soil Syst.* **4**: 9.
- Gupta, R., Jat, M. L. and Sharma, R. K. (2019). Conservation agriculture for sustainable intensification of rainfed systems in India. *Soil Tillage Res.* **195**: 104365. doi:10.1007/978-981-96-3392-0_13.
- ICAR (2021). *Handbook of Climate Smart Agriculture in India*. Indian Council of Agricultural Research, New Delhi, India.
- IPCC (2023). *Climate Change 2023: Synthesis Report*. Intergovernmental Panel on Climate Change. Cambridge University Press, Geneva, Switzerland.
- Jat, H. S., Kumar, A., Sutaliya, J. M., Kumar, S., Choudhary, M., Yadvinder Singh and Jat, M. L. (2019). Conservation agriculture-based sustainable intensification of basmati rice-wheat system in North-West India. *Arch. Agron. Soil Sci.* **65**: 1370-1386. doi:10.1080/03650340.2019.1566708.
- Kuai, J., Li, X., Ji, J., Li, Z., Xie, Y., Wang, B. and Zhou, G. (2022). Response of leaf carbon metabolism and dry matter accumulation to density and row spacing in two rapeseed genotypes. *Crop J.* **10**: 680-691.
- Kumar, S., Meena, R. S., Lal, R., Singh Yadav, G., Mitran, T., Meena, B. L. and EL-Sabagh, A. (2018). Role of legumes in soil carbon sequestration. In: *Legumes for Soil Health and Sustainable Management*. pp. 109-138.
- Lal, R. (2020). Soil carbon sequestration for climate change mitigation and food security. *Soil Sci. Soc. Am. J.* **84**: 857-877.
- Li, S. and Tasnady, D. (2023). Biochar for soil carbon sequestration: Current knowledge,

- mechanisms and future perspectives. **9**: 67.
- Li, Y., Ming, B., Fan, P., Liu, Y., Wang, K., Hou, P. and Xie, R. (2022). Quantifying contributions of leaf area and longevity to leaf area duration under increased planting density and nitrogen input regimens during maize yield improvement. *Field Crops Res.* **283**: 108551. doi:10.1016/j.fcr.2022.108551.
- Liao, Y., Cao, H. X., Liu, X., Li, H. T., Hu, Q. Y. and Xue, W. K. (2021). By increasing infiltration and reducing evaporation, mulching can improve the soil water environment and apple yield of orchards in semi-arid areas. *Agric. Water Manag.* **253**: 106936.
- Liu, C., Plaza-Bonilla, D., Coulter, J. A., Kutcher, H. R., Beckie, H. J., Wang, L. and Gan, Y. (2022). Diversifying crop rotations enhances agro ecosystem services and resilience. *Adv. Agron.* **173**: 299-335.
- Lorenz, K. and Lal, R. (2018). Carbon sequestration in agricultural ecosystems. **2018**: 978-983. doi: 10.1007/978-3-319-92318-5.
- Ma, K., Zhou, Y., Ma, Y. and Zhang, T. (2023). Improving stay-green traits and related physiological metabolism increased the rice yield under long-term warming in cool region. **2023**. DOI:10.21203/rs.3.rs-3312526/v1
- Ma, K., Zhou, Y., Ma, Y. and Zhang, T. (2024). Increased rice yield by improving the stay-green traits and related physiological metabolism under long-term warming in cool regions. *Int. J. Plant Prod.* **18**: 175-186.
- Ma, T., Zhu, S., Wang, Z., Chen, D., Dai, G., Feng, B. and Feng, X. (2018). Divergent accumulation of microbial necromass and plant lignin components in grassland soils. *Nat. Commun.* **9**: 3480. doi:10.1038/s41467-018-05891-1.
- Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A. and Winowiecki, L. (2017). Soil carbon 4 per mille. *Geoderma* **292**: 59-86.
- Nair, P. K. R., Kumar, B. M. and Nair, V. D. (2019). Agro-forestry as a climate change adaptation and mitigation strategy. *Agrofor. Syst.* **93**: 1-10.
- Pahari, A., Banerjee, H. and Banik, A. (2025). Soil and environmental improvement in intensive cereal-based cropping systems through crop residue management. *SATSA Mukhapatra* **29**: 78.
- Panchal, P., Preece, C., Peñuelas, J. and Giri, J. (2022). Soil carbon sequestration by root exudates. *Trends Plant Sci.* **27**: 749-757.
- Parvin Banu, A., Sujatha, K., Geetha, R. and Kannan, P. (2022). Biochar coating and its effect on seed quality and biochemical parameters in black gram (*Vigna mungo* L.) var. VBN 11. *Pharma Innov.* **11**: 2836-2840.
- Paustian, K., Larson, E., Kent, J., Marx, E. and Swan, A. (2019). Soil C sequestration as a biological negative emission strategy. *Front. Clim.* **1**: 8. https://doi.org/10.3389/fclim.2019.00008
- Prasad, R. S. and Sud, R. (2019). Implementing climate change adaptation: Lessons from India's National Adaptation Fund on Climate Change (NAFCC). *Clim. Policy* **19**: 354-366.
- Razzaq, A., Kaur, P., Akhter, N., Wani, S.H. and Saleem, F. (2021). Next-generation breeding strategies for climate-ready crops. *Front. Plant Sci.* **12**: 620420.
- Reddy, A. (2018). *Impact Study of Soil Health Card Scheme*. National Institute of Agricultural Extension Management (MANAGE), Hyderabad, India. pp. 106.
- Satlewal, A., Agrawal, R., Bhagia, S., Das, P. and Ragauskas, A. J. (2018). Rice straw as a feedstock for biofuels: Availability, recalcitrance and chemical properties. *Biofuels Bioprod. Biorefin.* **12**: 83-107.
- Singh, R., Bhattacharyya, R., Das, T. K., Sharma, A. R. and Jat, M. L. (2020). Crop residue management for soil health improvement and climate change mitigation. *Environ. Sustain.* **3**: 131-146.
- Smith, P. (2019). Interlinkages between climate change and land. In: *IPCC Special Report on Climate Change and Land*.
- Ullah, M. S., Malekian, R., Randhawa, G. S., Gill, Y. S., Singh, S., Esau, T. J. and Farooque, A. A. (2024). The potential of biochar incorporation into agricultural soils to promote sustainable agriculture: A critical review. *Rev. Environ. Sci. Biotechnol.* **23**: 1105-1130.
- World Bank. (2023). *State and Trends of Carbon Pricing 2023*. World Bank Group, Washington, DC, USA.
- Yang, F., Sui, L., Tang, C., Li, J., Cheng, K. and Xue, Q. (2021). Sustainable advances on phosphorus utilization in soil via addition of biochar and humic substances. *Sci. Total Environ.* **768**: 145106. doi:10.1016/j.scitotenv.2021.145106.
- Zhang, K., Han, X., Fu, Y., Zhou, Y., Khan, Z., Bi, J. and Luo, L. (2023). Biochar coating as a cost-effective delivery approach to promoting seed quality, rice germination and seedling establishment. *Plants* **12**: 3896.
- Zomer, R. J., Trabucco, A., Bossio, D. A. and Verchot, L. V. (2016). Climate change mitigation through conservation agriculture. *Agric. Ecosyst. Environ.* **220**: 164-174. doi:10.1016/j.agee.2016.01.001.