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**Annappa NN**
Ph.D. Scholar, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bangalore, Karnataka, India

**R Krishna Murthy**
Professor and Scheme Head, AICRP on STCR, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka, India

**Bhavya N**
Research Associate, AICRP on STCR, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka, India

**Shivakumara MN**
Research Associate, AICRP on STCR, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka, India

**Govinda K**
Senior Research Fellow, AICRP on STCR, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka, India

**Uday Kumar SN**
Senior Research Fellow, Indo-German Project, AICRP on STCR, Department of Soil Science and Agricultural Chemistry, College of Agriculture, GKVK, UAS, Bangalore, Karnataka, India

**Corresponding Author:**
**R Krishna Murthy**
Professor and Scheme Head, AICRP on STCR, Department of Soil Science and Agricultural Chemistry, UAS, GKVK, Bengaluru, Karnataka, India

# Understanding soil organic carbon dynamics in dryland ecosystems: A comprehensive review

**Annappa NN, R Krishna Murthy, Bhavya N, Shivakumara MN, Govinda K and Uday Kumar SN**

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**Abstract**
Soil organic carbon (SOC) is an essential component of the Earth's carbon cycle, significantly influencing soil fertility and productivity. The level of SOC in the soil depends on the equilibrium between carbon inputs-such as plant residues and organic amendments-and losses through microbial activity and respiration. SOC exists in diverse pools, including active or labile, intermediate, and stable or passive forms, each contributing uniquely to soil properties. Its stability and distribution are shaped by various factors, including climatic conditions, vegetation types, and land management strategies. Dryland soils, characterized by limited rainfall and high evapotranspiration, typically exhibit low organic matter content, resulting in poor fertility. The harsh environmental conditions, combined with high evaporation rates, often exacerbate issues like salinization, further degrading soil quality. Increasing SOC levels in these regions is vital for enhancing soil health and productivity. Agroforestry, which involves integrating trees and shrubs into farming systems, offers a viable approach for improving carbon sequestration in drylands. Specific strategies such as using leguminous trees, applying mulches, adopting cover cropping, and minimizing tillage can effectively boost carbon storage in these soils, enhancing their fertility, resilience, and overall sustainability.

**Keywords:** Soil organic carbon (SOC), dryland soils, agroforestry, carbon sequestration

## Introduction

Soil organic carbon (SOC) is essential for maintaining soil fertility, particularly in rainfed arid, semiarid, and sub-humid regions where limited water availability and harsh climatic conditions dominate [1]. SOC plays a critical role in sustaining agricultural productivity and preventing soil degradation in these environments. However, intensive cropping systems and poor rainwater management practices have led to significant losses of soil organic matter (SOM), resulting in degraded soil quality, nutrient deficiencies, and reduced productivity [2].

SOC is closely associated with SOM and exists in active and passive pools. The active pool, which includes living microorganisms, has a short turnover rate, while the passive pool is more stable and decomposes over a longer timeframe [3, 4]. Unlike inorganic carbon, which contributes to decomposition processes and salinity issues, SOC is essential for improving soil quality, enhancing food production, and reducing atmospheric CO2 levels [3]. Increasing SOC stocks is crucial for improving soil health and sustaining agricultural productivity, particularly in rainfed regions. Practices that effectively enhance SOC involve increasing organic inputs, slowing SOM decomposition, and minimizing SOC oxidation [5, 6].

Despite the recognized significance of SOC in improving soil quality and supporting agricultural systems, the dynamics of SOC in rainfed regions are not yet fully understood. Key aspects, such as the factors driving SOC loss and the most effective strategies for enhancing SOC stocks in these challenging conditions, require further investigation. Addressing these knowledge gaps is vital for developing sustainable agricultural practices to improve soil health and ensure long-term productivity in rainfed ecosystems [6].

This research aims to explore the dynamics of soil organic carbon in rainfed arid, semiarid, and sub-humid regions of India, focusing on identifying the primary factors affecting SOC levels and assessing the impact of conservation agriculture practices. By addressing the unique challenges and potential opportunities for increasing SOC in these regions, the study seeks to provide insights that can aid in developing strategies to combat soil degradation, enhance soil fertility, and support sustainable agricultural productivity amid increasing demands and environmental challenges.

**Soil organic carbon and carbon stock**

Soil serves as the largest terrestrial reservoir of carbon, holding approximately two-thirds of the Earth's terrestrial carbon [7], with about 1500 Gt of organic carbon stored in the top one meter of soil [8]. The soil organic carbon (SOC) pool is estimated to contain 1500 Pg of carbon within the first meter, which surpasses the carbon present in the atmosphere (around 800 Pg) and terrestrial vegetation (500 Pg) combined. SOC represents a key component of the global carbon cycle, which involves the continuous exchange of carbon among the soil, vegetation, oceans, and atmosphere. The SOC reservoir is dynamic, with carbon constantly cycling between various global carbon pools in different molecular forms. The amount of SOC in any soil depends on the balance between carbon inputs (such as organic matter additions) and outputs, including carbon dioxide released through microbial respiration and, to a lesser extent, dissolved organic carbon (DOC) lost through leaching. At local levels, soil erosion or deposition also contributes to the redistribution of carbon across local, landscape, and regional scales.

According to Srinivasarao *et al*. (2009) [9], *Vertisols* and related soils have higher carbon stocks compared to other soil types, followed by *Inceptisols, Alfisols*, and *Aridisols*. SOC content tends to be higher than inorganic carbon in *Alfisols* and *Aridisols*, while *Vertisols* and *Inceptisols* generally contain more inorganic carbon than SOC.

SOC is divided into different pools as a function of its physical and chemical stability [10].

1. **Fast pool (labile or active pool):** After addition of fresh organic carbon to the soil, decomposition results in a large proportion of the initial biomass being lost in 1-2 years.
2. **Intermediate pool:** Comprises microbially processed organic carbon that is partially stabilized on mineral surfaces and/or protected within aggregates, with turnover times in the range 10-100 years.
3. **Slow pool (refractory or stable pool):** Highly stabilized SOC, enters a period of very slow turnover of 100 to >1 000 years.

**Soil Organic Carbon Fractions**

**a) Particulate Organic Carbon (POC)**

This is the coarse fraction of soil organic matter, consisting primarily of particles smaller than 53 µm. It represents an intermediate stage between fresh plant residues and humified organic matter, forming a relatively stable carbon pool. POC serves as an important source of available carbon and acts as a key indicator of soil quality.

**b) Water-Soluble Carbon (WSC)**

This fraction is highly degradable by microorganisms and plays a significant role in nutrient transport. It contributes to soil formation and influences biogeochemical processes. WSC is also involved in redistributing organic carbon at different soil depths.

**c) Microbial Biomass Carbon (MBC)**

MBC represents the living component of soil organic matter, accounting for approximately 2% of the total organic matter. Although its proportion is small, it plays a critical role in soil functions and processes, often underestimated in importance.

**d) Permanganate Oxidizable Carbon (POXC)**

This fraction includes reactive organic carbon that is easily broken down by microorganisms. POXC is closely linked to particulate organic carbon and microbial biomass carbon and is highly sensitive to changes in management practices. It serves as an indicator for assessing the effects of cropping systems and soil management on soil organic matter.

**e) Humic Substances**

Humic substances are relatively stable, high-molecular-weight compounds with a characteristic brown to black coloration. They are formed through secondary synthesis reactions and include components such as humic acid, fulvic acid and humin. These substances play a vital role in improving soil structure and long-term carbon sequestration.

**Effect of different management practices on soil organic carbon dynamics**

**Tillage practices**

Conventional tillage practices in dryland areas often result in significant carbon loss through oxidation, which reduces soil organic carbon (SOC) levels and subsequently diminishes soil fertility. Tillage disrupts soil aggregates, exposing stabilized carbon to microbial decomposition, leading to carbon release as carbon dioxide [11]. In contrast, conservation tillage minimizes soil disturbance and carbon losses, while the incorporation of crop residues helps to enhance SOC levels.

Intensive agricultural practices involving frequent tillage accelerate the decline of SOC. The extent to which SOC is depleted or increased under continuous cultivation depends on factors such as carbon losses due to oxidation, the quality and quantity of crop residues returned to the soil, and the addition of organic amendments. No-tillage (NT) systems retain crop residues on the soil surface, reducing soil disturbance and supporting the accumulation or maintenance of SOC, unlike conventional tillage (CT) systems [11]. NT systems also influence soil organic matter (SOM), microbial communities, and nutrient availability.

Kumar *et al*. (2014) [12] observed that tillage reduced aggregate stability and physical protection of SOM, resulting in rapid decomposition by heterotrophic microorganisms. Their findings showed significantly higher SOC levels in NT soils compared to CT soils, particularly in the 0-10 cm depth. Similar trends were noted for total nitrogen (TN) and the C/N ratio. Additionally, drainage influenced SOC, TN, and the C/N ratio at this depth.

Prasad *et al*. (2016) [13] reported that reduced tillage intensity and nitrogen source selection significantly affected oxidizable carbon fractions. At the 0-20 cm depth, medium tillage (MT) combined with 100% organic sources (100% OS) showed higher oxidizable carbon levels compared to other tillage practices and nitrogen sources. They found that oxidizable carbon accounted for 23.1-24.7% of total organic carbon. Key labile SOC pools, such as particulate organic carbon (POC), microbial biomass carbon (MBC) and permanganate oxidizable carbon ($KMnO_4$-C), were higher in MT and 100% OS treatments compared to conventional tillage or inorganic nitrogen sources.

The improvement in labile carbon pools such as particulate organic carbon (POC), microbial biomass carbon (MBC), and permanganate oxidizable carbon (KMnO4-C) under medium tillage (MT) compared to conventional tillage (CT) in the surface soil (0-20 cm) was 47.6%, 16.0%, and 43.2%, respectively. Similarly, treatments using 100% organic sources (100% OS) exhibited increases of 37.5%, 23.1%, and 66.7% for these carbon fractions, respectively, compared to treatments with 100% inorganic organic sources (IOS). Surface soils generally showed greater concentrations of labile carbon pools than deeper layers [13]. Reduced tillage practices are well-established for enhancing labile carbon fractions, particularly in the upper soil layers [14].

Minimum tillage contributes to the development of active carbon pools, especially in the plough layer of legume-based cropping systems and in the lower soil profile of cereal-based systems. The dynamics of SOC fractions within the soil profile highlight the positive impacts of conservation tillage on soil quality [15].

Sandra Hermle *et al*. (2008) [16] reported that tillage had minimal impact on overall soil carbon stocks, SOC concentrations, and the distribution of carbon among different SOC fractions when considering equivalent soil masses. Their study found that carbon sequestration in no-tillage (NT) systems was not consistently higher than in tilled plots. Treatment-induced effects primarily altered the vertical distribution of carbon rather than the proportions of carbon among soil fractions.

The vertical distribution of SOC exhibited predictable patterns: NT and grassland (GL) systems accumulated the highest SOC levels near the soil surface, while ploughed soils showed a more uniform distribution of SOC across depths. Changes in carbon fractions were mainly associated with shifts in the intermediate fraction (aggregate-associated carbon). However, the presence of plant residues on the surface in NT systems encouraged the accumulation of labile particulate carbon compared to ploughed systems. Shallow tillage demonstrated clear advantages over ploughing, resulting in significantly higher amounts of all SOC fractions, while exhibiting no significant differences from NT.

## Cropping systems

Cropping systems play a crucial role in determining soil fertility in agricultural practices, as different systems contribute varying amounts of carbon to the soil. Incorporating forage crops into cropping systems can significantly enhance soil organic carbon (SOC) due to their higher biomass production, extensive root systems, and incorporation of crop residues.

The influence of cropping systems on SOC dynamics depends on factors such as crop type, cropping duration, and management practices. Including annual forage crops in rotation with cereals helps maintain both cereal and forage yields. Forages are harvested earlier for hay than cereals, which conserves soil moisture and supports subsequent crop yields [17, 18]. Rotating perennial legume forages with cereals enriches soil nitrogen and aids in weed and pest control [17]. Continuous cropping systems also contribute more crop residue to the soil, improving organic matter compared to crop-fallow rotations [19].

Upendra *et al*. (2011) [20] observed that growing forages in rotation, with or without durum wheat, influenced carbon inputs both above and below ground, as well as soil carbon fractions. Alfalfa cultivation resulted in higher SOC, particulate total carbon (PTC) at 0-15 cm depth, potential carbon mineralization (PCM), and microbial biomass carbon (MBC) at 0-120 cm depth compared to durum-forage rotations.

Moharana *et al*. (2017) found that different fractions of oxidizable organic carbon (VLC, LC, LLC, and NLC) under varying oxidation conditions followed the order: NLC > LLC > LC > VLC, except in specific systems like barley-fallow, mustard-moth bean, and chickpea-groundnut. In wheat-pearl millet systems, VLC constituted 17% of total organic carbon (TOC), while LC, LLC, and NLC accounted for 22%, 23%, and 38%, respectively [21].

Jiashu Chu *et al*. (2016) reported the highest recovery of organic carbon in continuous alfalfa systems, primarily in the >0.053 mm aggregate size class, which varied by cropping system. Continuous alfalfa led to the accumulation of carbon and nitrogen in the 0.25-2 mm and 0.053-0.25 mm size classes, with more stable carbon and nitrogen compared to continuous wheat or rotational systems. Similarly, Liebig *et al*. (2004) [22] noted greater SOC levels under switchgrass systems than in row-crop cultivation.

Mahdi and Jesse (2007) highlighted that microbial biomass carbon (MBC) in corn-soybean (CS) systems was approximately half of that in switchgrass systems (S5 and SA). The S5 system exhibited 20% more MBC than SA, attributed to higher detritus on the soil surface due to less frequent burning. Switchgrass systems, with their extensive root development, contributed significantly more carbon to the soil than corn-soybean rotations and enhanced subsoil MBC by approximately 200% compared to these rotations [23].

## Application of organic and inorganic fertilizer and crop residue incorporation

In agricultural systems, particularly under dryland conditions, incorporating crop residues and applying organic manures are critical for sustaining soil fertility and productivity over the long term. Organic manure application enhances soil organic carbon (SOC) through microbial decomposition of residues. Increased organic matter improves soil water-holding capacity, which is especially beneficial for dryland crops.

Enke Liu *et al*. (2013) [24] observed that particulate organic carbon (POC) was distributed along the soil depth, with higher concentrations in surface soils decreasing with depth. At the 0-20 cm depth, POC under treatments like NP+FYM (Farm Yard Manure), NP+S, and FYM alone was 103%, 89%, and 90% higher, respectively, than under the control (CK). Regardless of depth, NP+FYM consistently resulted in higher dissolved organic carbon (DOC) levels compared to other treatments, while CK and N treatments exhibited lower DOC contents. Microbial biomass carbon (MBC) also varied significantly across fertilizer treatments, with the SOC concentration in the 0-80 cm soil profile increasing notably with farmyard manure or straw application. The NP+FYM treatment led to an 82% higher mean MBC content compared to the CK treatment.

Adding organic matter is particularly effective at increasing SOC and soil fertility when initial SOC levels are below a critical threshold. However, maintaining or building SOC in Andosol croplands can be challenging due to their naturally high SOC content [25]. Intensified tillage and crop cycles can reduce soil organic matter (SOM), deteriorating soil structure [26]. Conversely, SOM accumulation can enhance soil structure, creating a positive feedback loop that supports SOM stocks and dynamics [27].

Salvatore Baiano and Luigi Morra (2017) [28] reported that compost application improved the mean weight diameter (MWD) of soil aggregates compared to mineral fertilization. However, the unfertilized control showed MWD values similar to those of organic fertilization plots, despite lower SOC concentrations. This could be due to reduced disruptive factors like root penetration in the unfertilized control. Compost application increased organic carbon (OC) content across all aggregate size classes, with SOC primarily accumulating in macroaggregates (>250 µm). Biowaste compost was more effective than mineral fertilization for long-term carbon sequestration by stabilizing carbon in the mineral-associated fraction (MOM) and enhancing soil structure in sandy loam soils.

Incorporating straw into semiarid soils significantly increased SOC storage, macroaggregate content (>0.25 mm), MWD, and geometric mean diameter (GMD). Higher rates of straw incorporation further enhanced these parameters, while fractal dimensions decreased with increasing straw addition. Thus, straw incorporation is an effective strategy for improving soil aggregate content and stability in semiarid regions [29].

Integrating summer green gram into a maize-chickpea cropping system is a promising approach for enhancing crop productivity, soil fertility, and energy efficiency. This system is closely followed by maize-mustard-green gram rotations. Cultivating summer green gram was most profitable under conventional tillage with crop residue addition. However, zero tillage offers additional benefits, such as improved soil aggregation, carbon sequestration, nitrogen availability, and environmental sustainability. While productivity and economic returns may be slightly lower under zero tillage, it is more energy-efficient and environmentally friendly [30].

In agricultural practices, particularly in dryland areas, the incorporation of crop residues and organic manure is vital for sustaining soil fertility and productivity over the long term. The decomposition of organic residues by microbes contributes to an increase in soil organic carbon (SOC), enhancing the soil's water-holding capacity, which is crucial for crops in dryland conditions.

Lisa Reiter (2015) [31] found that incorporating residues into the soil increased SOC stocks by 3.15 Mg ha$^{-1}$, although the effect was relatively modest compared to other studies. Fractionation analysis indicated that most carbon was retained in the fraction associated with clay and silt particles, with the greatest increase in this fraction after residue incorporation. This suggests that straw incorporation in clay soils may lead to a stable, long-term sequestration of carbon, even if management practices change.

The application of filter cake (a by-product of sugar processing) and municipal solid waste, combined with recommended NPK fertilizers, has been shown to significantly boost wheat grain yields, water use efficiency (WUE), and total organic carbon (TOC) in surface soils (0-15 cm). The recommended combination of 3 t C ha$^{-1}$ of both municipal solid waste and filter cake with NPK fertilizers has been suggested for use in wheat-maize cropping systems in Khyber Pakhtunkhwa to enhance productivity, WUE, and soil carbon status [32].

Lehtinen (2014) [33] demonstrated that long-term crop residue incorporation can increase crop yields. A positive relationship between crop residue incorporation and SOC concentration was observed over a period of more than 20 years in a continental climate. However, this practice also resulted in increased CO2 and N2O emissions, highlighting the need to maintain or increase SOC levels to protect soil properties like aggregate stability.

Integrated nutrient management (INM) is crucial for improving soil productivity in dryland areas. By providing essential nutrients, INM enhances both aboveground and belowground biomass, which contributes carbon to the soil. Root proliferation and root exudates boost microbial activity, leading to faster decomposition and higher SOC levels.

Using farmyard manure (FYM) alongside NPK fertilizers based on a soil test-based targeted yield (STCR) approach has been shown to increase soil fertility and SOC pools. Significant correlations between labile carbon (LBC), microbial biomass carbon (MBC), and crop yield suggest that these pools play a key role in nutrient turnover and plant nutrient availability. The Carbon Management Index indicates that INM is effective in enhancing crop productivity, nutrient availability, and soil carbon pools over the long term [34].

Sur *et al*. (2010) [35] found that organic carbon content significantly increased with different treatments compared to the control. The highest organic carbon content (0.88%) was observed when 4 tonnes per hectare of organic manure was applied alongside recommended NPK and zinc. Soil nutrients, including nitrogen (N), phosphorus (P), and potassium (K), also increased gradually with these treatments.

Long-term application of farmyard manure combined with NPK fertilizers to rice and brown sarson cropping systems improved both the physicochemical and biological properties of the soil. This practice significantly increased SOC, particulate organic carbon (POC), microbial biomass carbon (MBC), and other soil organic carbon fractions, thereby enhancing soil quality and crop productivity [36].

Kashyap *et al*. (2017) observed that the application of vermicompost improved soil organic stock, carbon sequestration rates, and nutrient uptake, especially in treatments using 100% recommended dose of fertilizer (RDF). The highest SOC and carbon sequestration values were recorded in the 100% RDF treatment, followed by 50% RDF combined with vermicompost, with the control showing the lowest values [37].

Lawrence Aula *et al*. (2016) [38] showed that manure application led to a significant increase in SOC, with values rising by 4.1 and 3.8 g kg-1 in 2013 and 2014 compared to the unfertilized check plot. Over the long term (1993-2014), SOC in the unfertilized plot decreased slightly, highlighting the importance of nutrient management in maintaining soil organic carbon levels.

In a six-year study, integrated nutrient treatments led to a 2.0-fold increase in SOC sequestration compared to fallow plots, indicating the potential of integrated approaches for long-term soil health and carbon sequestration. Among the different treatments, the highest easily wettable yield (EWY) was observed in $T_4$ (15.06 Mg ha$^{-1}$), followed by $T_5$ (11.76 Mg ha$^{-1}$) and $T_6$ (11.20 Mg ha$^{-1}$) [39].

**Water Management and Land Use**

Carbon dynamics in soils are influenced by both land use systems and water management practices. Land use impacts carbon stocks through vegetation, while water management affects the decomposition rate and distribution of carbon fractions within the soil. In dryland areas, where water is scarce and temperatures are high, carbon loss from the soil due to oxidation tends to be higher. Therefore, adopting water conservation practices and effective land use management is crucial for minimizing carbon loss.

Apesteguia *et al*. (2015) [39] found that a higher percentage of maize-derived organic carbon was present in irrigated maize (M-irr) compared to rainfed maize (M-rf), particularly in both large and small macro-aggregates. The largest proportion of maize-derived organic carbon was incorporated into the large macro-aggregates in both treatments.

Assize Toure *et al*. (2013) [40] observed that soil organic carbon (SOC) concentrations and stocks were greater under semi-natural savanna compared to groundnut fields. Crop cultivation resulted in a reduction in SOC levels, largely due to the removal of wood and other organic matter. In comparison to semi-natural savanna, SOC storage in groundnut fields was approximately 27% to 35% lower in the top 20 cm of soil. This decrease was not linked to soil texture, as similar trends were observed in soils with both low and high clay content.

**Agroforestry**

The integration of trees into cropping systems can significantly enhance soil carbon content and fertility. This improvement occurs due to the organic matter contributions from tree litterfall and fine roots. Kaur *et al*. (2000) [41] found that inputs from trees, particularly from litterfall and fine roots, increased soil organic matter content. The order of organic matter contribution varied among tree species, with Acacia contributing the most, followed by Populus and Eucalyptus. The levels of microbial biomass carbon and nitrogen ranged from 76.1 to 153.4 mg C $g^{-1}$ soil and 11.1 to 32.6 mg N $g^{-1}$ soil, respectively. Tree species had a significant impact on microbial carbon and nitrogen levels, with the integration of trees with crops showing a positive effect on microbial biomass. The increase in microbial biomass was observed to be 7%, 23%, and 15% for Acacia, Eucalyptus, and Populus systems, respectively. The microbial C:N ratio varied from 6.92 to 5.86 in Eucalyptus and Populus systems, while in Acacia-based systems, it ranged from 4.56 to 4.71.

Guibin Wang *et al*. (2015) [42] concluded that agroforestry systems are highly effective at restoring soil organic carbon (SOC) stocks in areas that were previously used for agriculture. Even afforestation with Ginkgo alone led to benefits, with systems showing higher total and SOC stocks compared to monocropping after nine years. The labile carbon fractions were particularly sensitive to changes in cultivation practices, with their increase following Ginkgo establishment indicating an improvement in soil quality.

Remi Cardinael *et al*. (2015) [43] demonstrated that agroforestry systems have the potential to increase SOC stocks. However, despite the deep rooting systems of trees, most additional SOC was concentrated in the topsoil layers and in labile organic fractions, which are more vulnerable. Tree rows were found to be a crucial factor for SOC storage in alley cropping systems. Combining agroforestry with no-till or permanent cover practices could effectively enhance SOC stocks. In addition, higher SOC in the inter-row areas could improve soil fertility, reduce the need for chemical fertilizers, and indirectly lower greenhouse gas emissions.

Over more than 10 years, agroforestry practices have notably improved soil quality compared to rubber monoculture. These improvements included better soil aggregation, increased carbon and nitrogen accumulation, and better distribution of SOC and nitrogen within aggregates. Aggregate formation was linked to higher carbon storage, and the macroaggregate fraction (>0.25 mm) contained more organic carbon and nitrogen than the microaggregate fraction [44]. Additionally, the presence of the A. caven tree positively influenced microbial biomass, respiration rate, light fraction, and SOC levels, with values being higher under its canopy than outside. However, microbial biomass carbon was lower under the canopy of all agroforestry systems compared to natural forests (NF) at depths of up to 10 cm [45].

**Carbon sequestration in dryland agriculture**

Carbon sequestration refers to the process of increasing carbon content in both soils and plants, which is essential for reducing atmospheric carbon dioxide levels. Plants are crucial for carbon fixation as they absorb carbon during photosynthesis and store it in the form of carbohydrates. In contrast, soils receive carbon from various sources and store it in different forms and fractions. The importance of carbon sequestration is particularly significant in dryland areas, as it enhances organic carbon levels in the soil, which is vital for improving soil fertility and boosting crop production.

There are two main strategies for increasing soil organic carbon (SOC) sequestration in cropland soils: (1) restoring degraded soils and ecosystems, and (2) applying recommended agricultural practices to prime soils. Restoring degraded soils increases biomass production, enhances SOC content, and improves water quality. Various management practices have the potential to sequester carbon in dryland ecosystems.

Drylands are characterized by several features that limit their carbon sequestration potential. The most prominent factor is the scarcity of water, which significantly reduces plant productivity and, consequently, the accumulation of carbon in the soil. This issue is further exacerbated by low and often erratic rainfall patterns. Efficient management of available water is therefore crucial. Additionally, SOC levels tend to decrease with rising temperatures, further complicating carbon sequestration efforts in drylands [46].

The soil carbon pool is vital for maintaining soil quality, ensuring the availability of plant nutrients, supporting environmental functions, and contributing to the global carbon cycle. Drylands, which typically have low fertility and minimal organic matter, are particularly suited for carbon sequestration efforts.

Srinivasarao *et al*. (2009) [9] found that organic carbon stocks in soils were significantly influenced by rainfall amounts, with legume-based cropping systems contributing to higher organic carbon sequestration. Long-term experiments using manure under rainfed conditions resulted in slight improvements in organic carbon levels. However, many dryland farmers lack access to manure or crop residue, which limits their ability to enhance soil carbon. Therefore, alternative strategies such as minimum tillage, green manuring, cover cropping, using green leaf manure (e.g., Gliricidia), composting farm waste, vermicomposting, and incorporating legumes into the cropping system may help improve carbon stocks in Indian soils.

Combining chemical fertilizers with farmyard manure (FYM) can increase crop yields and enhance carbon sequestration in *Alfisols* of southern India. To maintain SOC levels, it requires an annual input of 1.62 Mg C $ha^{-1}$ year-1. However, the availability of FYM or crop residues at sufficient levels is often a challenge in this region. Thus, a balanced use of NPK fertilizers, along with modest amounts of FYM or crop residues, is a practical and sustainable approach to ensure continued crop production while promoting carbon sequestration [47].

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**Conflict of Interest**

No conflict of interest.

**Conclusion**

This study emphasizes the importance of soil organic carbon (SOC) in improving soil quality and supporting food production, especially in dryland areas. The results highlight those agricultural practices such as conservation tillage, proper fertilization, crop rotation, and agroforestry integration play a significant role in influencing SOC dynamics. These practices help to increase SOC stocks by promoting biomass growth, reducing carbon losses due to oxidation, and enhancing carbon sequestration. The research contributes valuable insights by showing that the adoption of sustainable farming practices can reduce soil degradation in drylands, leading to healthier soils and improved long-term agricultural productivity. These findings have practical significance for farmers and policymakers focused on boosting soil carbon stocks in dryland regions, thus improving resilience to climate change and securing food production. However, the study does have some limitations, including the variation in SOC responses to different management practices across diverse soil types and climates. Future research should prioritize long-term field studies to gain a deeper understanding of how SOC dynamics interact with various management techniques in different dryland environments. Additionally, examining the socioeconomic factors that affect the adoption of these practices will offer a more holistic approach to promoting sustainable land management.

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