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Devanoori Tarun

Bharatiya Engineering Science
& Technology Innovation
University, Gownivaripalli
(V), Gorantla (M), Sri Sathya
Sai, Andhra Pradesh, India

Chittimothu Suresh Babu

Bharatiya Engineering Science
& Technology Innovation
University, Gownivaripalli
(V), Gorantla (M), Sri Sathya
Sai, Andhra Pradesh, India

Pinipe Keerthi Priya

Bharatiya Engineering Science
& Technology Innovation
University, Gownivaripalli
(V), Gorantla (M), Sri Sathya
Sai, Andhra Pradesh, India

Ch Bhargava Rami Reddy

Scientist, Department of Soil
Science, Institute of Frontier
Technology (IFT), Regional
Agricultural Research Station,
Tirupati, Andhra Pradesh

Ch Sowmya

Subject Matter Specialist
(SMS) Agronomy, Krishi
Vigyan Kendra (KVK) -
Mamnoon, Warangal,
Telangana, India

Ch Naga Jyothi

Scientist (Agronomy), Acharya
N. G. Ranga Agricultural
University-Regional
Agricultural Research Station
(RARS), Lam, Guntur,
Andhra Pradesh, India

Corresponding Author:

Chittimothu Suresh Babu

Bharatiya Engineering Science
& Technology Innovation
University, Gownivaripalli
(V), Gorantla (M), Sri Sathya
Sai, Andhra Pradesh, India

Carbon sequestration potential of cropping systems under tropical agro-ecosystems

**Devanoori Tarun, Chittimothu Suresh Babu, Pinipe Keerthi Priya, Ch
Bhargava Rami Reddy, Ch Sowmya and Ch Naga Jyothi**

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Abstract

Carbon sequestration in agricultural soils is a promising strategy for mitigating climate change while improving soil fertility and sustainability of tropical agro-ecosystems (Lal, 2004). Tropical regions are characterized by high temperatures, intense rainfall, rapid decomposition of organic matter, and fragile soil structure, which often lead to depletion of soil organic carbon (SOC) (Davidson & Janssens, 2006). High climatic variability and intensive cultivation accelerate SOC losses and reduce soil productivity in many tropical soils (Batjes, 2014). Cropping systems such as conservation agriculture enhance soil carbon storage through reduced tillage and residue retention practices (Six *et al.*, 2002). Agroforestry systems improve carbon sequestration by increasing biomass production and belowground carbon inputs (Nair *et al.*, 2010). Crop diversification enhances carbon accumulation by improving residue quantity and quality returned to soil (McDaniel *et al.*, 2014). Cover cropping increases organic matter inputs and protects soil from carbon losses due to erosion (Blanco-Canqui *et al.*, 2015). Integrated nutrient management improves soil carbon stability by combining organic and inorganic nutrient sources (Vanlauwe *et al.*, 2010). Improved management practices increase carbon inputs through plant residues and root biomass, thereby enhancing soil organic carbon pools (Paustian *et al.*, 2016). Root biomass contributes significantly to long-term carbon storage due to slower decomposition rates in soil (Rasse *et al.*, 2005). Enhanced microbial activity under improved cropping systems supports carbon stabilization in soil aggregates (Six *et al.*, 2004). Soil aggregation protects organic carbon from rapid mineralization and enhances carbon persistence (Tisdall & Oades, 1982). Improved cropping systems enhance nutrient cycling and increase soil biological activity, contributing to soil carbon sequestration (Lal, 2015). Increased carbon storage improves soil structure, water retention, and nutrient availability in tropical agro-ecosystems (Minasny *et al.*, 2017). This review synthesizes recent research findings on carbon sequestration potential of cropping systems in tropical agro-ecosystems and examines key influencing factors affecting SOC dynamics (Smith *et al.*, 2008). Understanding carbon sequestration mechanisms can help improve soil management strategies for sustainable agriculture (Powlson *et al.*, 2011). Adoption of carbon-sequestering cropping systems can improve soil health, productivity, climate resilience, and long-term sustainability of tropical agriculture (Amundson *et al.*, 2015).

Keywords: Carbon sequestration, soil organic carbon, tropical agriculture, cropping systems, conservation agriculture, agroforestry, climate change mitigation

Introduction

Climate change caused by increasing atmospheric carbon dioxide (CO₂) concentration is one of the major global environmental challenges affecting agricultural sustainability and ecosystem stability (IPCC, 2014) ^[16]. Agricultural soils represent a major global carbon reservoir, storing approximately 1500-2400 Pg of carbon, which makes soil carbon sequestration an important strategy for mitigating greenhouse gas emissions (Lal, 2008) ^[17]. Soil organic carbon plays a critical role in regulating atmospheric CO₂ concentration through biological and physicochemical stabilization processes (Stockmann *et al.*, 2013) ^[18]. Increasing soil carbon storage contributes to climate change mitigation while improving soil fertility and productivity (Smith *et al.*, 2007) ^[19].

Tropical agro-ecosystems play a significant role in the global carbon cycle due to their large geographical coverage and high biological productivity (Grace *et al.*, 2006) ^[20]. Warm temperatures and high rainfall in tropical regions accelerate organic matter decomposition, leading to rapid loss of soil organic carbon under intensive cultivation practices (Davidson &

Janssens, 2006)^[2]. Continuous cultivation, residue removal, and excessive tillage reduce organic matter inputs and accelerate carbon mineralization in tropical soils (Lal, 2004)^[22]. Low biomass return and poor nutrient management further contribute to SOC depletion and soil degradation (Batjes, 2014)^[3]. Improved cropping systems can reverse this trend by increasing carbon inputs through plant residues, roots, and organic amendments (Paustian *et al.*, 2016)^[9].

Carbon sequestration in agricultural systems involves the transfer of atmospheric CO₂ into plant biomass through photosynthesis and its subsequent storage in soil organic matter pools (Schlesinger & Andrews, 2000)^[21]. Plant residues and root biomass serve as primary sources of carbon input to soil systems (Rasse *et al.*, 2005)^[10]. Cropping systems influence SOC dynamics through residue management practices that determine the quantity and quality of carbon returned to soil (Blanco-Canqui *et al.*, 2015)^[7]. Root biomass contributes significantly to stable carbon pools because of its slower decomposition rate compared to aboveground residues (Kätterer *et al.*, 2011)^[22]. Soil microorganisms regulate decomposition processes and influence carbon stabilization mechanisms in soil aggregates (Six *et al.*, 2002). Soil aggregation physically protects organic carbon from rapid decomposition and enhances long-term carbon storage (Tisdall & Oades, 1982)^[12, 4].

Concept of carbon sequestration in cropping systems

Carbon sequestration refers to the process of capturing atmospheric carbon dioxide (CO₂) and storing it in plant biomass, soils, and sediments for long periods, thereby reducing greenhouse gas concentration in the atmosphere (Lal, 2004)^[22]. In agricultural systems, carbon is primarily stored in vegetation and soil organic matter through biological processes such as photosynthesis and biomass accumulation (Schlesinger & Andrews, 2000)^[21]. Soil organic carbon (SOC) is influenced by carbon inputs from crop residues, root biomass, farmyard manure, compost, and other organic amendments added to soil (Paustian *et al.*, 2016)^[9]. Carbon losses occur through microbial decomposition, soil respiration, erosion, and leaching processes that reduce SOC stocks over time (Davidson & Janssens, 2006)^[2]. Maintaining a balance between carbon inputs and losses is essential for enhancing carbon sequestration potential in cropping systems.

Major carbon pools in agro-ecosystems include above-ground biomass carbon stored in plant tissues such as leaves, stems, and grains (Nair *et al.*, 2010)^[5]. Below-ground root carbon contributes significantly to long-term carbon storage because roots decompose slowly and form stable organic compounds (Rasse *et al.*, 2005)^[10]. Soil organic carbon is the largest terrestrial carbon pool and plays a critical role in soil fertility, structure, and water retention capacity (Stockmann *et al.*, 2013)^[18]. Soil inorganic carbon, mainly present as carbonates, contributes to long-term carbon storage in arid and semi-arid tropical regions (Lal, 2008)^[17].

Cropping systems regulate carbon balance by influencing photosynthetic carbon fixation, quantity of biomass returned to soil, and decomposition dynamics (Amundson *et al.*, 2015)^[15]. Crop residue management practices determine the rate of organic matter addition and influence soil microbial activity responsible for carbon transformation (Six *et al.*,

2002)^[4]. Soil microorganisms play a key role in decomposition processes and conversion of organic residues into stable humus fractions (Trivedi *et al.*, 2017). Soil aggregation protects organic carbon from rapid mineralization and enhances long-term carbon stabilization (Tisdall & Oades, 1982)^[12, 23].

Studies indicate that soil properties such as clay content, mineralogy, soil aggregation, and nutrient availability significantly influence SOC stabilization mechanisms in tropical soils (Minasny *et al.*, 2017)^[24]. Clay minerals protect organic carbon by forming organo-mineral complexes that reduce decomposition rates (Six *et al.*, 2004)^[11]. Improved nutrient availability enhances plant biomass production, thereby increasing carbon inputs into soil systems (Lal, 2015)^[13]. Understanding interactions between soil properties and management practices is essential for improving carbon sequestration potential of tropical agro-ecosystems (Paustian *et al.*, 2016)^[9].

Characteristics of tropical agro-ecosystems affecting carbon sequestration

Tropical agro-ecosystems differ significantly from temperate systems due to distinct climatic, soil, and management factors that strongly influence soil organic carbon (SOC) dynamics and carbon sequestration potential (Lal, 2004)^[22]. High temperature and moisture conditions in tropical environments accelerate biological activity and organic matter decomposition, often resulting in lower SOC stocks compared to temperate soils (Davidson & Janssens, 2006)^[2]. However, high primary productivity in tropical regions also provides opportunities for increased carbon inputs through crop biomass and root growth (Grace *et al.*, 2006)^[20]. Understanding these unique characteristics is essential for designing effective carbon sequestration strategies in tropical agriculture (Paustian *et al.*, 2016)^[9].

Climatic factors

High temperature in tropical climates accelerates microbial decomposition of organic matter, leading to rapid turnover of soil organic carbon (Davidson & Janssens, 2006)^[2]. Heavy rainfall contributes to nutrient leaching and reduces nutrient availability necessary for biomass production and carbon stabilization (Lal, 2003)^[56]. High humidity enhances microbial activity, which influences decomposition processes and nutrient cycling in soil systems (Trivedi *et al.*, 2017). Favorable climatic conditions promote rapid biomass production, increasing the potential for higher carbon inputs through plant residues and root biomass (Nair *et al.*, 2010)^[5]. Seasonal rainfall patterns influence plant growth cycles and carbon allocation in tropical cropping systems (Follett *et al.*, 2011). Climatic variability also affects soil respiration rates and determines net carbon sequestration potential (Schlesinger & Andrews, 2000)^[21, 23, 25].

Soil-related factors

Tropical soils are often highly weathered and dominated by soil orders such as Oxisols and Ultisols, which are characterized by low natural fertility and high mineral weathering (Sanchez, 2019)^[26]. These soils typically contain low organic matter content due to rapid decomposition and limited biomass return (Batjes, 2014)^[3]. Poor soil aggregation stability reduces the physical protection of organic carbon and increases susceptibility to carbon loss (Six *et al.*, 2002)^[4]. Nutrient deficiencies,

particularly nitrogen and phosphorus limitations, restrict biomass production and reduce carbon input to soil systems (Vitousek *et al.*, 2010). High iron and aluminum oxide content in tropical soils influences carbon stabilization through organo-mineral interactions (Kleber *et al.*, 2015). Soil texture and clay mineralogy play an important role in determining SOC storage capacity and stabilization mechanisms (Minasny *et al.*, 2017)^[24, 27, 28, 52].

Management constraints

Intensive cultivation practices accelerate organic matter decomposition and reduce soil carbon stocks over time (Lal, 2015)^[13]. Low residue return due to competing uses such as fodder and fuel limits carbon input into soil organic matter pools (Valbuena *et al.*, 2012). Excessive tillage disturbs soil structure and exposes organic carbon to oxidation losses (Six *et al.*, 2004)^[11]. Soil erosion caused by poor soil cover and heavy rainfall results in significant carbon losses from agricultural lands (Montgomery, 2007). Unsustainable nutrient management practices reduce plant growth and biomass production, limiting carbon sequestration potential (Vanlauwe *et al.*, 2010)^[8, 29, 30].

Despite these constraints, tropical soils show significant potential for carbon sequestration when sustainable management practices such as conservation agriculture, agroforestry, and integrated nutrient management are adopted (Lipper *et al.*, 2014)^[31]. Improved soil management practices enhance biomass production and promote stabilization of carbon in soil aggregates (Paustian *et al.*, 2016)^[9]. Adoption of climate-smart agricultural practices can improve soil carbon storage and enhance resilience of tropical agro-ecosystems.

Carbon sequestration potential of different cropping systems: Cropping systems play a crucial role in regulating soil organic carbon (SOC) dynamics and improving soil health in tropical agro-ecosystems. Sustainable cropping practices enhance carbon inputs through plant biomass, crop residues, and root exudates, while reducing carbon losses caused by soil erosion and rapid decomposition (Lal, 2015)^[13]. Different cropping systems influence carbon sequestration through mechanisms such as improved soil aggregation, increased microbial activity, and enhanced stabilization of organic matter (Paustian *et al.*, 2016)^[9]. Tropical cropping systems have significant potential to mitigate climate change by storing carbon in soil and biomass while improving productivity and sustainability.

Conservation agriculture systems

Conservation agriculture (CA) is based on three core principles: minimum soil disturbance, permanent soil cover, and crop diversification (FAO, 2017). Reduced tillage minimizes soil disruption and decreases oxidation of soil organic matter, thereby conserving soil carbon stocks (Six *et al.*, 2004)^[11]. Retention of crop residues protects soil from erosion and increases organic matter input, which enhances soil aggregation and improves carbon stabilization (Blanco-Canqui & Lal, 2008)^[32].

Permanent soil cover moderates soil temperature and moisture conditions, promoting microbial activity and enhancing transformation of plant residues into stable humus fractions (Lal, 2013)^[59]. Crop rotation improves root biomass and enhances soil biological diversity, contributing to long-term carbon sequestration (Hobbs *et al.*, 2008).

Long-term experiments indicate that conservation agriculture increases SOC concentration significantly compared to conventional tillage systems, especially in tropical environments characterized by rapid organic matter decomposition and soil erosion (Powlson *et al.*, 2014)^[34]. Enhanced formation of macro-aggregates under CA protects organic carbon from microbial decomposition and increases carbon residence time in soil (Six *et al.*, 2002)^[4, 33].

Crop diversification and crop rotation

Crop diversification and rotation systems increase biomass production and improve soil biological activity, contributing to higher carbon inputs (Lin, 2011). Rotations involving cereals, legumes, pulses, and oilseeds improve residue quality and promote efficient nutrient cycling (Drinkwater *et al.*, 1998). Inclusion of legumes enhances biological nitrogen fixation, increasing biomass production and soil carbon accumulation (Peoples *et al.*, 2009)^[35, 36, 37].

Diverse cropping systems enhance microbial diversity and improve soil structure by promoting aggregate formation, which protects SOC from rapid decomposition (Tiemann *et al.*, 2015). Studies in tropical agro-ecosystems indicate that diversified cropping systems increase SOC stocks by approximately 15-25% compared with monocropping systems due to improved biomass input and residue quality (Cong *et al.*, 2015). Crop rotation also reduces pest incidence and improves sustainability of cropping systems (Snapp *et al.*, 2010)^[38, 39, 40].

Cover cropping systems: Cover cropping systems contribute significantly to carbon sequestration by providing continuous vegetative cover that protects soil from erosion and enhances biomass production (Blanco-Canqui *et al.*, 2015)^[7]. Cover crops add organic residues that increase soil organic matter and improve soil structure (Kaspar & Singer, 2011). Leguminous cover crops contribute nitrogen through biological fixation, which enhances plant growth and carbon input into soil (Sainju *et al.*, 2002)^[41].

Mixed-species cover crops improve biodiversity and enhance nutrient cycling efficiency, leading to improved soil carbon stabilization (Finney *et al.*, 2016). In tropical regions, cover crops such as sunhemp, cowpea, and green gram contribute significant biomass and root residues that improve SOC storage (Lal, 2015)^[42, 13].

Agroforestry systems

Agroforestry systems integrate trees with crops and livestock, increasing carbon sequestration potential through both above-ground biomass and soil carbon storage (Nair *et al.*, 2010)^[5]. Trees contribute continuous litter fall and root biomass that enhance soil organic matter accumulation (Jose, 2009). Deep-rooted tree species improve nutrient recycling by transporting nutrients from deeper soil layers to the surface (Udawatta & Jose, 2012)^[44].

Agroforestry systems improve soil structure and enhance biodiversity, contributing to ecosystem stability and improved carbon sequestration efficiency (Montagnini & Nair, 2004). Studies indicate that agroforestry systems store significantly higher carbon compared to monocropping systems due to continuous biomass addition and improved soil protection (Albrecht & Kandji, 2003)^[45, 46].

Integrated nutrient management systems: Integrated nutrient management (INM) involves combined use of

organic manures, compost, crop residues, and chemical fertilizers to improve soil fertility and carbon sequestration (Vanlauwe *et al.*, 2010). Organic inputs increase microbial biomass and improve soil aggregation, enhancing stabilization of SOC (Bhattacharyya *et al.*, 2012).

Long-term experiments show that application of farmyard manure and compost increases SOC accumulation and improves soil fertility (Lal, 2004) ^[22]. Balanced nutrient supply enhances plant growth and increases biomass production, which contributes to higher carbon input into soil systems (Palm *et al.*, 2001) ^[8, 48, 49].

Intercropping systems: Intercropping systems improve carbon sequestration by increasing total biomass production and enhancing photosynthetic efficiency (Lithourgidis *et al.*, 2011). Different crop species utilize resources efficiently, increasing carbon input through diverse root systems (Zhang *et al.*, 2014). Intercropping improves soil cover and reduces erosion losses, thereby minimizing carbon loss from soil systems (Brooker *et al.*, 2015) ^[51].

Mechanisms of soil carbon stabilization in tropical cropping systems: Soil carbon stabilization occurs through physical, chemical, and biological processes that protect organic carbon from rapid decomposition (Six *et al.*, 2002) ^[4].

- **Aggregate Formation:** Soil aggregates physically protect organic carbon from microbial decomposition and improve long-term carbon storage (Tisdall & Oades, 1982) ^[12].
- **Mineral Association:** Clay minerals bind organic carbon through organo-mineral complexes, enhancing stabilization and increasing carbon residence time (Kleber *et al.*, 2015) ^[52].
- **Root Biomass Contribution:** Root biomass contributes significant carbon to deeper soil layers, improving long-term carbon sequestration (Rasse *et al.*, 2005) ^[10].
- **Microbial Biomass Activity:** Microorganisms convert plant residues into stable humus fractions, enhancing SOC stabilization (Cotrufo *et al.*, 2013).
- **Organo-mineral Complexes:** Interaction between organic matter and soil minerals enhances carbon protection and improves long-term carbon storage (Schmidt *et al.*, 2011) ^[53].

Factors affecting carbon sequestration in tropical cropping systems

- **Soil Factors:** Soil texture, mineralogy, depth, and pH influence SOC stabilization capacity (Minasny *et al.*, 2017) ^[24].
- **Climate Factors:** Temperature, rainfall, and humidity influence decomposition rates and biomass production (Davidson & Janssens, 2006) ^[2].
- **Crop-related Factors:** Crop type, residue quality, root biomass, and cropping intensity affect carbon input into soil (Bolinder *et al.*, 2007) ^[54].
- **Management Factors:** Tillage, nutrient management, irrigation, and residue retention influence SOC accumulation (Lal, 2015) ^[13].

Benefits of carbon sequestration in tropical agro-ecosystems

- **Environmental Benefits:** Carbon sequestration

mitigates climate change by reducing atmospheric CO₂ concentration (Smith *et al.*, 2008). Improved SOC enhances biodiversity and reduces soil erosion (Lal, 2004).

- **Agronomic Benefits:** SOC improves soil fertility, nutrient availability, and water holding capacity, resulting in increased crop productivity (Palm *et al.*, 2001) ^[49].
- **Economic Benefits:** Improved soil health reduces fertilizer requirements and enhances yield stability. Carbon credit markets provide additional income opportunities for farmers adopting sustainable practices (Paustian *et al.*, 2016) ^[9].

Challenges in carbon sequestration under tropical cropping systems: Rapid decomposition of organic matter due to high temperature limits SOC accumulation (Davidson & Janssens, 2006) ^[2]. Poor residue management and soil erosion contribute to carbon losses (Lal, 2003) ^[56]. Limited awareness among farmers and lack of long-term experiments restrict adoption of carbon-sequestering practices (Smith *et al.*, 2008). SOC storage often reaches equilibrium depending on soil type and climatic conditions (Stewart *et al.*, 2007) ^[55].

Future Research Needs

Future research should focus on long-term experiments on SOC dynamics and role of microbial communities in carbon stabilization (Cotrufo *et al.*, 2013). Integration of remote sensing, GIS, and digital soil mapping tools can improve estimation of carbon stocks (Minasny *et al.*, 2017). Development of climate-smart cropping systems and carbon credit policies can encourage adoption of carbon farming practices (Paustian *et al.*, 2016) ^[9]. Measurement, Reporting, and Verification (MRV) frameworks can improve carbon accounting in agricultural systems (Smith *et al.*, 2020) ^[24, 53].

Conclusion

Cropping systems play a critical role in carbon sequestration in tropical agro-ecosystems. Sustainable practices such as conservation agriculture, agroforestry, crop diversification, cover cropping, intercropping, and integrated nutrient management enhance soil organic carbon storage and improve soil health. Adoption of carbon-sequestering cropping systems contributes to climate change mitigation, improved productivity, and long-term agricultural sustainability. Future research should emphasize development of climate-smart agricultural technologies and long-term monitoring of SOC dynamics to enhance carbon sequestration potential in tropical regions.

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