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Carbon sequestration in vegetable crops

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Abstract

Climate change, primarily driven by escalating greenhouse gas (GHG) concentrations, poses an existential threat to global food security and ecosystem stability. Carbon sequestration - the biological, geological and technological capture of atmospheric CO₂ - has been identified as a critical mitigation strategy. Vegetable crops, characterized by rapid growth rates, high photosynthetic efficiency, intensive cultivation cycles and substantial below-ground biomass inputs, represent an underexplored yet significant natural carbon sink within agricultural systems. This review comprehensively examines (i) the mechanisms of carbon sequestration in vegetable cropping systems, including photosynthetic carbon fixation, root exudation and residue decomposition; (ii) the major types of carbon sequestration (terrestrial, geological, oceanic, technological and industrial); (iii) key soil-plant factors influencing soil organic carbon (SOC) accumulation and (iv) evidence-based management practices such as organic farming, biochar application, conservation tillage and integrated nutrient management that enhance SOC stocks in vegetable systems. Empirical data from multiple field studies demonstrate that vegetable crops can sequester 91.79-3,095.99 kg C ha⁻¹ season⁻¹ in plant biomass, while management interventions can increase SOC sequestration by 1.18-5.48 Mg C ha⁻¹ yr⁻¹. Organic vegetable farming systems store 24.52% more SOC than conventional systems and biochar application at 40 Mg ha⁻¹ increases SOC content by up to 35.8%. Carbon markets and climate policy frameworks provide economic incentives for adopting sequestration-enhancing practices. Integrating vegetable cropping systems into climate-smart agriculture represents a viable, multi-functional pathway toward achieving net-zero emission goals and sustainable food production.

Keywords: Soil organic carbon, vegetable crops, biochar, organic farming, climate change mitigation, photosynthesis, carbon markets, conservation agriculture

1. Introduction

Global climate change is driven principally by the progressive accumulation of greenhouse gases (GHGs) - primarily carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) - in the Earth's atmosphere. The combustion of fossil fuels, deforestation, land-use change and intensified agricultural practices have collectively elevated atmospheric CO₂ concentrations from pre-industrial levels of approximately 280 ppm to over 420 ppm in 2024 (IPCC, 2023). The global mean surface temperature has risen by approximately 1.42°C above pre-industrial baselines, making the decade 2015-2024 the warmest on record. Projections under current policy trajectories indicate a potential warming of 2.8°C by 2100, far exceeding the 1.5°C threshold stipulated under the Paris Agreement (UNFCCC, 2015).

In 2024, global GHG emissions reached a record high of 53.2 Gt CO₂ equivalent - a 1.3% increase over 2023. Among sectors, the power industry accounted for nearly 30% of total global emissions. Agriculture, forestry and other land use collectively contribute approximately 22% of global GHG emissions, with a significant proportion originating from soil management, enteric fermentation, rice cultivation and biomass burning. Importantly, the agricultural sector possesses one of the greatest potentials to offset anthropogenic emissions through carbon sequestration.

Carbon sequestration - the process of capturing atmospheric CO₂ and storing it in stable biological, geological or engineered reservoirs - has been recognized as a cost-effective complement to emission reduction strategies. Among terrestrial approaches, soil carbon sequestration is one of the most promising and economically viable options, capable of sequestering 0.14-0.57 Pg C per year globally (Lal, 2004). Agricultural soils alone can potentially sequester up to 1.2 billion metric tonnes of carbon annually (IPCC, 2019) [47, 27, 20].

Vegetable crops, while underrepresented in carbon sequestration literature relative to forests and major grain crops, offer distinct advantages. Their rapid growth rates, high photosynthetic efficiency, intensive cropping cycles and substantial organic residue production position them as recurrent, short-term but cumulative carbon sinks. Vegetable systems further contribute to SOC through root exudates,

crop residue incorporation and the application of organic amendments such as compost, manure and biochar. With vegetable cultivation covering approximately 58 million hectares globally and expanding under urbanization and dietary shifts, quantifying and enhancing the carbon sequestration role of these crops.

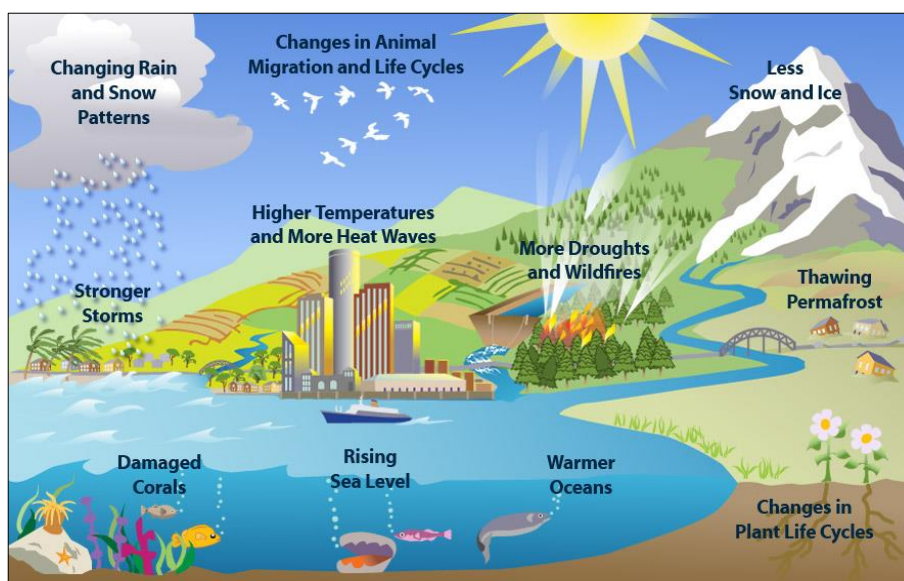


Fig 1: Effects - Global warming

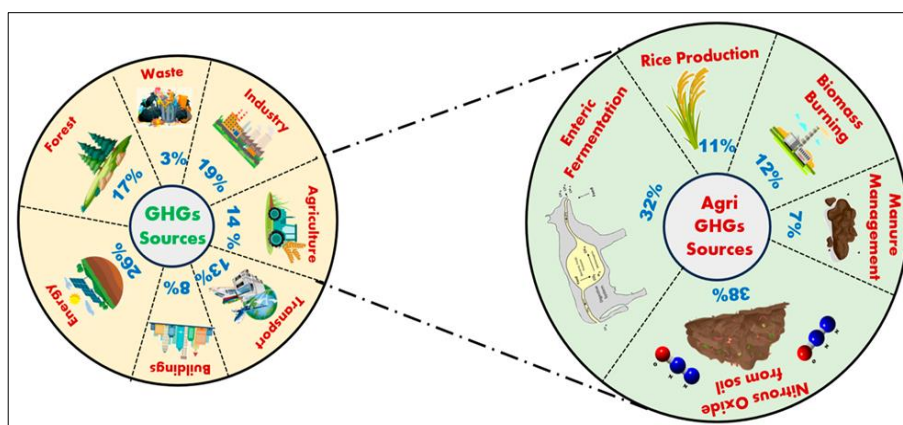


Fig 2: GHG - Sources

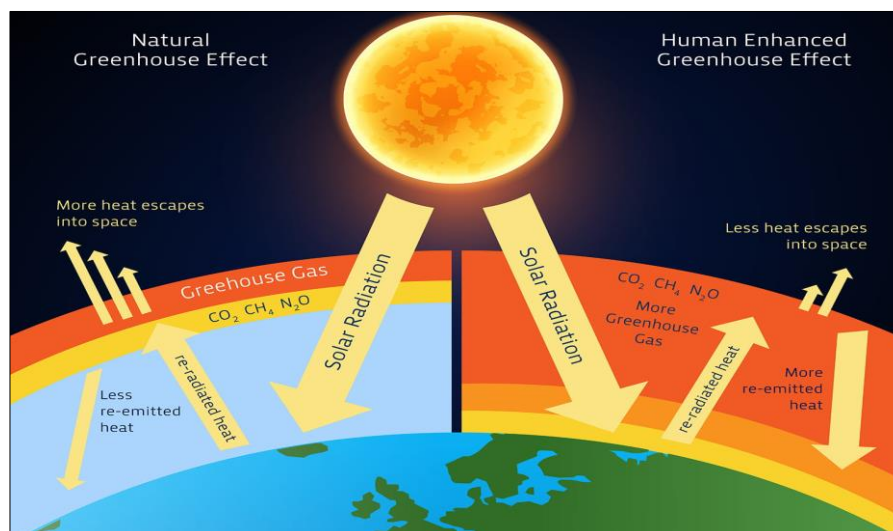


Fig 3: Effects - GHG

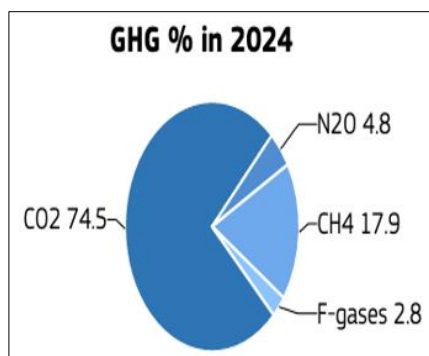


Fig 4: Composition of GHG

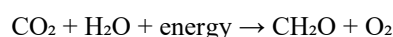
This review synthesizes current knowledge on carbon sequestration mechanisms in vegetable cropping systems, evaluates the influencing factors, examines evidence-based management interventions and discusses policy and economic dimensions including carbon markets. The aim is to provide a comprehensive scientific basis for integrating vegetable crops into climate-smart agriculture frameworks.

2. The carbon cycle and carbon pools

Carbon is the fourth most abundant element in the Universe and the structural backbone of all living organisms. The movement of carbon between biotic and abiotic reservoirs constitutes the global carbon cycle, which operates through two interconnected components: the slow (geological) carbon cycle and the fast (biological) carbon cycle.

2.1 The Slow Carbon Cycle: The slow carbon cycle operates over geological timescales of 100-200 million years. Atmospheric CO₂ dissolves in rainwater to form carbonic acid (H₂CO₃), which chemically weathers silicate rocks, releasing calcium (Ca²⁺) and magnesium (Mg²⁺) ions. These ions are transported by rivers to the oceans, where they combine with bicarbonate to form calcium carbonate (CaCO₃) - the principal mineral in coral skeletons, marine shells and limestone. Burial of organic carbon in marine sediments eventually forms fossil fuels, while CO₂ is returned to the atmosphere through volcanic eruptions at a rate of 130-380 million metric tonnes per year. By comparison, human activities release approximately 30 billion tonnes of CO₂ annually (ie.) 100-300 times more than volcanic emissions.

2.2 The Fast Carbon Cycle: The fast carbon cycle, operating on timescales of days to decades, is predominantly biological. Plants and phytoplankton absorb atmospheric CO₂ during photosynthesis and convert it into organic compounds *via* the Calvin cycle:



The organic carbon fixed in plant biomass enters food chains through consumption and returns to the atmosphere through respiration and decomposition. Between 10¹⁵ and 10¹⁷ grams of carbon cycle through the biosphere annually. Vegetable crops are integral participants in this fast cycle, fixing carbon repeatedly across multiple cropping seasons.

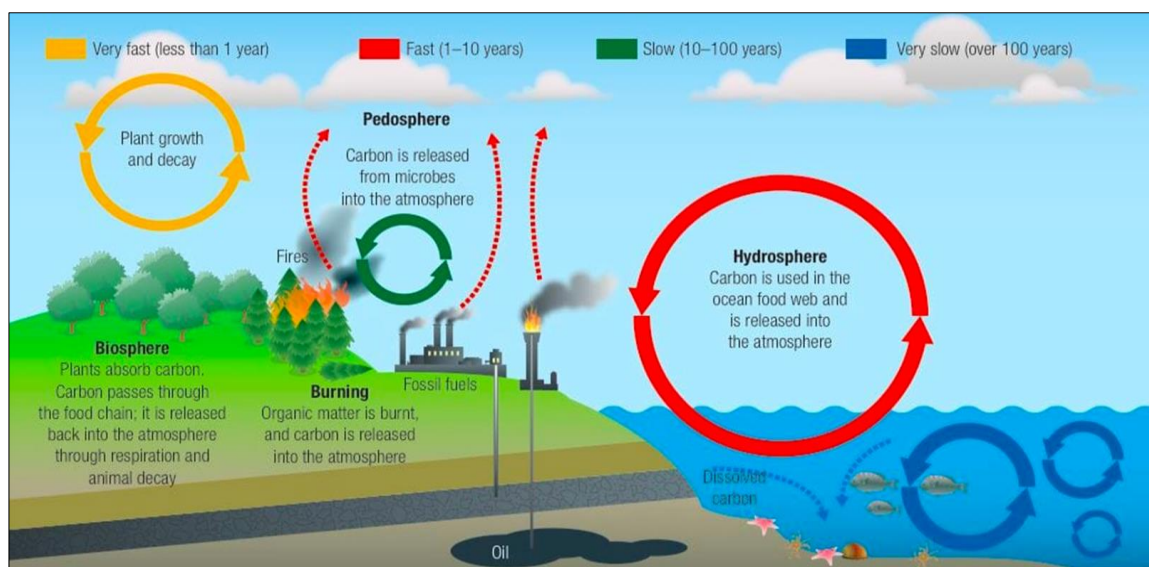


Fig. 5. Slow and fast carbon cycle

2.3 Carbon Pools

The global carbon cycle involves four major pools: (i) the atmosphere (860 Gt C as CO₂ and CH₄); (ii) the oceans (38,000 Gt C, primarily as dissolved inorganic carbon); (iii) terrestrial ecosystems (2,500 Gt C in soils and 650 Gt C in living vegetation); and (iv) geological reservoirs (65,500 billion metric tonnes in rocks, sediments and fossil fuels). Carbon exchange among these pools, known as carbon fluxes, determines the atmospheric concentration of CO₂. Perturbation of any reservoir - through deforestation, fossil

fuel combustion or agricultural degradation - shifts carbon into the atmosphere, intensifying the greenhouse effect.

3. Carbon sequestration-concept and types

Carbon sequestration is defined as the long-term removal, capture and storage of atmospheric CO₂ in biological, geological or engineered reservoirs, thereby reducing net atmospheric GHG concentrations. It is distinct from carbon capture at the point of emission. Table 1 summarizes the key distinctions between carbon capture and carbon sequestration.

Table 1: Comparison of Carbon Capture and Carbon Sequestration

Parameter	Carbon Capture	Carbon Sequestration
Emission Reduction	Captures CO ₂ after fuel combustion, preventing its direct release into the atmosphere.	Removes CO ₂ directly from the atmosphere and stores it in natural or engineered reservoirs.
Methods	Pre-combustion capture, post-combustion capture and oxy-fuel combustion technologies.	Biological sequestration (plants, soils, forests) and geological sequestration (underground rock formations).
Timescale	Short-term; continuous process linked to combustion.	Long-term; carbon stored for decades to centuries.
Cost & Feasibility	Capital-intensive and energy-demanding; limited global adoption due to policy and economic constraints.	Establishment and long-term maintenance of carbon sinks are complex but cost-effective relative to DAC technologies.

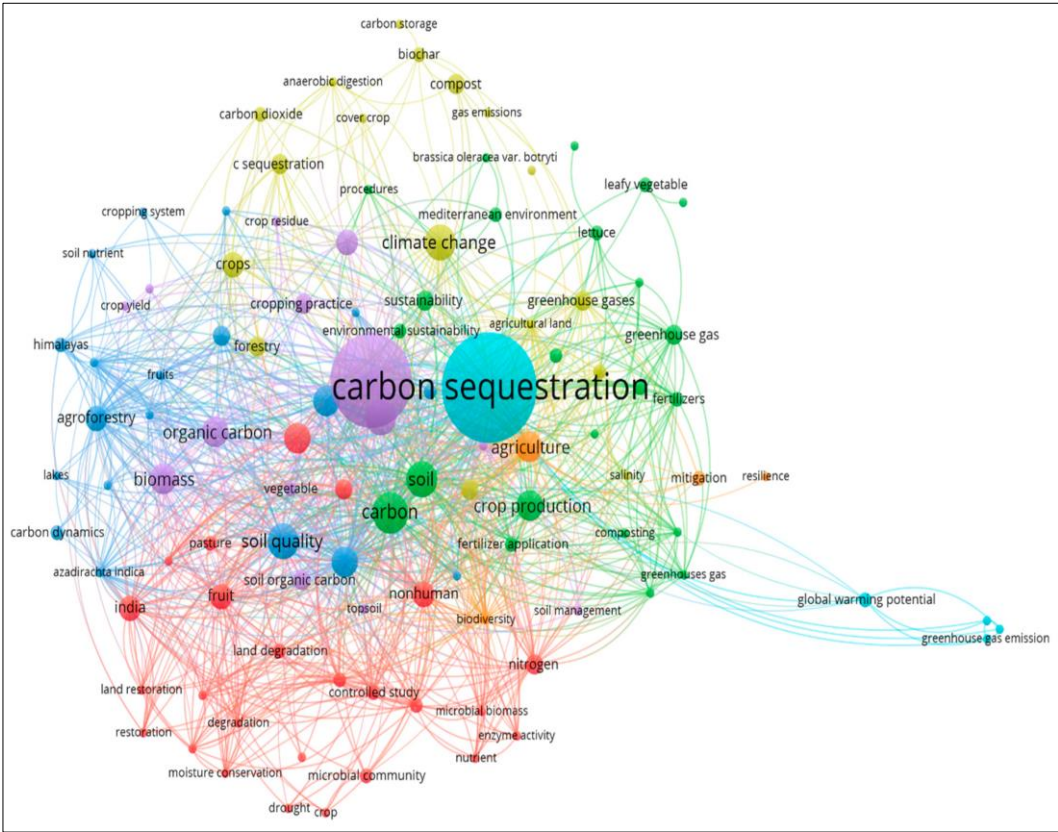


Fig.6. Network visualization on recent hotspots

Carbon sequestration encompasses multiple approaches ranging from natural biological processes to advanced industrial and technological solutions. Table 2 provides a

systematic overview of the principal sequestration methods relevant to both agricultural and industrial contexts.

Table 2: Major Carbon Sequestration Methods and Descriptions

S. No.	Method	Description
1	CO ₂ Chemical Conversion	Conversion of CO ₂ into value-added chemicals such as methanol, urea or polymers using suitable catalysts.
2	CO ₂ Fuels Production	Production of synthetic fuels like methanol by combining captured CO ₂ with renewable hydrogen.
3	Microalgae Utilization	High-efficiency CO ₂ fixation by microalgae to produce biofuels and value-added biochemicals.
4	CO ₂ in Building Materials	Use of CO ₂ in cement curing or aggregate production, partially replacing conventional cement.
5	CO ₂ -Enhanced Oil Recovery (EOR)	Injection of CO ₂ into oil reservoirs to enhance oil recovery while simultaneously storing CO ₂ underground.
6	BECCS	Integration of biomass growth, bioenergy production and CO ₂ capture to achieve net-negative emissions.
7	Enhanced Weathering	Accelerated carbonate formation by spreading crushed silicate rocks (e.g., basalt) on agricultural land.
8	Forestry and Wood Products	Utilization of timber from managed forests to store atmospheric CO ₂ in long-lived wood products and buildings.
9	Soil Carbon Sequestration	Adoption of land-management practices that enhance agricultural productivity while increasing soil organic carbon stocks.
10	Biochar Application	Application of pyrolyzed biomass (biochar) to soils for long-term carbon storage and improved soil health.

3.1 Terrestrial Carbon Sequestration

Terrestrial sequestration involves the capture of CO₂ by plants through photosynthesis and its subsequent storage in plant biomass and soil organic matter. Plants store approximately 45% of their dry mass as carbon. Through above-ground and below-ground biomass accumulation, vegetable crops contribute to both short-term (biomass) and long-term (soil) carbon pools. Soil can additionally store carbon as inorganic carbonates in the form of 'caliche', which can persist for over 70,000 years in arid soils - substantially longer than soil organic matter, which typically retains carbon for several decades.

3.2 Geological Carbon Sequestration

Geological (or subsurface) carbon sequestration involves the capture and injection of CO₂ into deep underground formations, including depleted oil and gas reservoirs, saline aquifers and coal seams. Physical trapping within rock pores and chemical mineralization provide long-term storage. CO₂-enhanced oil recovery (EOR) is a commercial application in which CO₂ injection improves oil extraction while simultaneously storing CO₂ underground. The United States currently utilizes approximately 32 million tonnes of CO₂ annually for EOR. Oxyfuel combustion and pre- and post-combustion capture are the principal industrial techniques for concentrating CO₂ for geological storage.

3.3 Oceanic Carbon Sequestration

Oceans represent the largest active carbon sink, holding approximately 50 times more CO₂ than the atmosphere. The marine biological pump, driven by phytoplankton photosynthesis, transfers approximately 11 billion tonnes of carbon to the deep ocean annually. Dissolved inorganic carbon (DIC) in surface waters is consumed by phytoplankton and upon death, this organic material sinks as marine snow, transporting carbon to seafloor sediments. Polar regions are particularly active ocean carbon sinks due to cold, nutrient-rich conditions. However, increased oceanic CO₂ uptake reduces ocean pH (acidification), threatening marine biodiversity.

3.4 Technological Carbon Sequestration

Emerging technological approaches include Direct Air Capture (DAC), which mechanically extracts CO₂ from ambient air at a current cost of \$500-800 per tonne; graphene synthesis from CO₂ as a value-added industrial pathway and Bioenergy with Carbon Capture and Storage (BECCS), which integrates biomass combustion with CO₂ capture to achieve net-negative emissions. Enhanced weathering, the application of crushed silicate rocks (basalt) to agricultural soils to accelerate CO₂ mineralization is a promising but nascent strategy receiving increasing research attention.

4. Soil organic carbon sequestration in vegetable systems

4.1 Mechanisms of Soil Carbon Sequestration

Soil organic carbon (SOC) sequestration begins with the photosynthetic fixation of atmospheric CO₂ into plant biomass. Carbon enters the soil through four principal pathways: (i) aboveground litter deposition; (ii) below-ground root biomass turnover; (iii) root exudation of soluble carbon compounds and (iv) microbial biomass necromass accumulation. Approximately 30-50% of total SOC

originates from below-ground inputs, underscoring the critical role of root systems in carbon stabilization.

Once in the soil, organic carbon undergoes decomposition by microbial communities. An estimated 60-70% of carbon in plant residues is mineralized to CO₂ within one year (Six *et al.*, 2006). The residual fraction is transformed into humus, a complex mixture of lignin-derived compounds, microbial metabolites and organo-mineral complexes, which can persist in soil for decades to centuries. The rate of humification is governed by the C:N ratio of residues: vegetable crops possess narrow C:N ratios of 9-24 (compared with 58 for wheat), facilitating rapid humification and higher SOC accumulation rates.

Carbon stabilization in soil occurs through three overlapping mechanisms: (i) biochemical protection via recalcitrant compounds such as lignin and suberin; (ii) physical protection within soil macro- and micro-aggregates; and (iii) chemical stabilization through adsorption onto clay mineral surfaces and formation of organo-mineral complexes. The relative contributions of these mechanisms depend on soil texture, pH, microbial community composition and management practices.

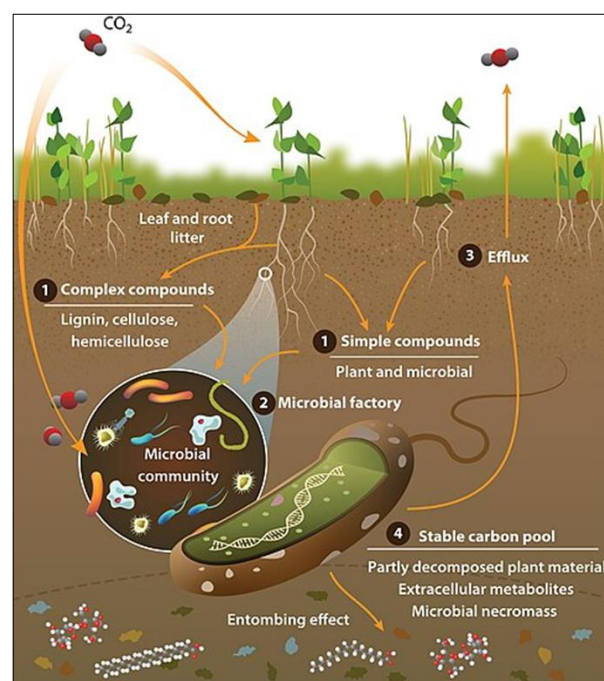


Fig 7: Soil carbon cycle

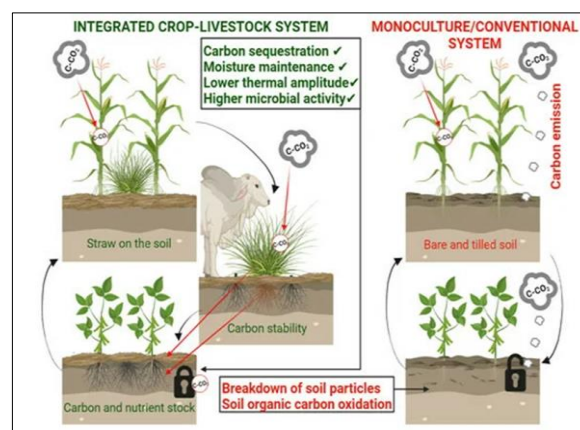


Fig 8: Integrated and conventional crop system in soil carbon sequestration

4.2 Factors Influencing SOC Sequestration in Vegetable Systems

SOC sequestration in vegetable cropping systems is regulated by an interplay of soil physical and chemical properties, land management practices, climatic conditions

and vegetation characteristics. Table 3 provides a comprehensive synthesis of these influencing factors with their estimated percentage contributions to SOC dynamics, based on published meta-analyses and long-term field studies.

Table 3: Influencing Factors for Soil Organic Carbon Sequestration in Agricultural Systems

Factor	% Contribution	Description	References
A. Soil Properties (30% contribution)			
Soil Texture	15%	Clay-rich soils sequester carbon by protecting organic materials from microbial degradation.	Churchman <i>et al.</i> , 2014 ^[7]
Soil Structure	—	Well-aggregated soils facilitate organic matter-stabilizing microenvironments.	Dalal <i>et al.</i> , 2020 ^[5]
Soil pH	5%	Optimal pH (6-7) promotes microbial activity and nutrient availability, improving sequestration.	Bhattacharyya <i>et al.</i> , 2020 ^[13]
Soil Moisture & Temperature	10%	Moist soils and moderate temperatures enhance microbial activity and carbon stabilization.	Dignac <i>et al.</i> , 2017; Knicker <i>et al.</i> , 2007 ^[25]
B. Land Management Practices (40% contribution)			
Tillage Practices	10%	Conservation tillage increases soil carbon by up to 57% over conventional tillage.	Sharma <i>et al.</i> , 2016 ^[44]
Crop Rotation & Diversification	10%	Cover crop rotations boost soil organic carbon by 20% over monocultures.	Duval <i>et al.</i> , 2016 ^[14]
Organic Amendments	10%	Adding compost and manure increases soil carbon content and reserves over time.	Diacono <i>et al.</i> , 2011 ^[12]
Agroforestry	10%	Adding trees to agricultural areas increases biomass; agroforestry systems store 1.5 Mg C ha ⁻¹ yr ⁻¹ .	Lorenz <i>et al.</i> , 2014 ^[32]
Perennial Cropping Systems	10%	Deep root systems of perennial crops (e.g., switchgrass) store soil carbon effectively on marginal lands.	Das <i>et al.</i> , 2018 ^[8]
C. Climate Conditions (20% contribution)			
Temperature & Precipitation	15%	Warm, wet climates boost plant production and soil carbon accumulation.	Davidson <i>et al.</i> , 2006 ^[9]
Extreme Weather Events	5%	Droughts, floods and storms damage soil structure and vegetation, reducing carbon sequestration.	Saco <i>et al.</i> , 2021 ^[42]
D. Vegetation Types (10% contribution)			
Grasslands	4%	Extensive root systems and continuous ground cover make grasslands significant carbon sinks.	Lorenz <i>et al.</i> , 2018 ^[33]
Forests	4%	Forest soils may store up to 2.0 Mg C ha ⁻¹ yr ⁻¹ depending on species, age and management.	Jandl <i>et al.</i> , 2007 ^[22]
Wetlands	2%	Slow decomposition makes wetlands strong carbon habitats; peatlands trap up to 5.5 Mg C yr ⁻¹ .	Iqbal <i>et al.</i> , 2020 ^[21]

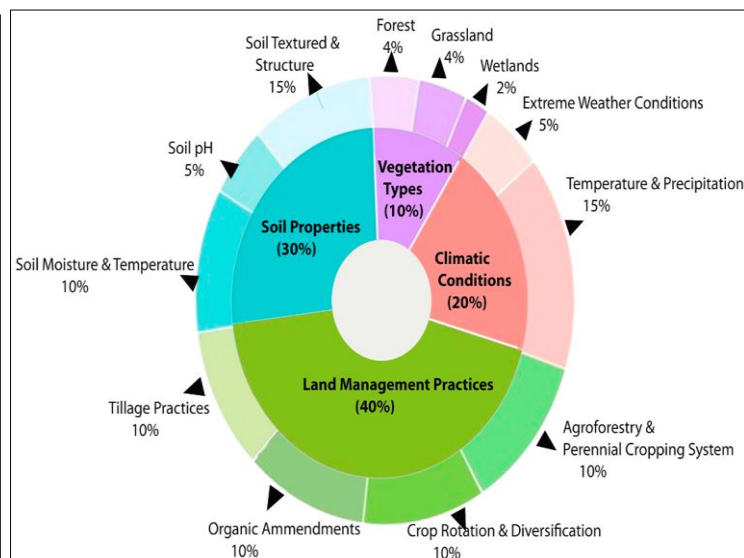
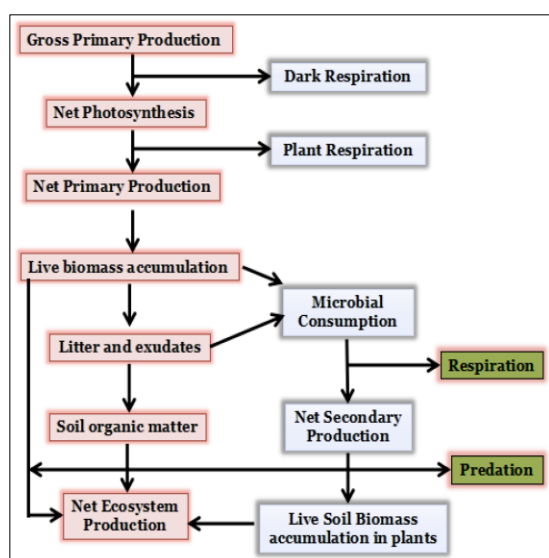


Fig 9: Mechanism of carbon sequestration, **Fig 10:** Factors influencing soil carbon sequestration

4.3 Agricultural Technologies for Enhancing SOC

Multiple agronomic technologies have been demonstrated to enhance SOC stocks in vegetable systems. These include:

- **Cropping Intensification:** Elimination of fallow periods and adoption of multiple cropping cycles

increases annual biomass inputs and residue additions, cumulatively contributing to SOC accumulation, particularly when complemented with organic inputs.

- **Conservation Tillage:** Reduced disturbance of soil structure preserves macro- and micro-aggregates, which

- physically protect organic matter from decomposition. Conservation tillage has been reported to increase SOC by up to 57% over conventional tillage (Sharma *et al.*, 2016).
- **Liming and Nutrient Management:** Maintaining optimal soil pH (6-7) enhances microbial activity and enzymatic humification. Balanced fertilization promotes plant biomass production, increasing carbon returns to the soil.
 - **Perennial Vegetation and Agroforestry:** Incorporating perennial plants and trees into vegetable systems significantly increases root biomass, fungal-dominated decomposition pathways and soil aggregation, all of which enhance long-term SOC storage. Agroforestry systems can store 1.5 Mg C ha⁻¹ yr⁻¹ (Lorenz *et al.*, 2014) ^[32].
 - **Microbial Manipulation:** Inoculation with arbuscular mycorrhizal fungi (AMF) and plant growth-promoting rhizobacteria (PGPR) enhances root-driven SOC inputs and promotes the formation of stable organo-mineral complexes, improving carbon stabilization. Table 4 summarizes the key management practices for increasing SOC through both reduced carbon loss and enhanced carbon inputs.

Table 4: Management Practices for Increasing SOC in Vegetable Agricultural Systems

Management Practice	Effect on Soil Carbon
Reduced tillage / No-tillage	Reduced C loss; preserved soil aggregates protect organic matter from decomposition.
Erosion control (contour ploughing, terracing)	Reduced C loss; prevents physical removal of topsoil rich in organic carbon.
Addition of organic amendments (compost, manure, crop residues)	Increased C input; direct addition of organic carbon enhances SOC accumulation.
Use of cover crops	Both reduced C loss and increased C input; cover crops protect soil and add organic biomass.
Agroforestry integration	Increased C input; tree biomass and root systems significantly augment SOC stocks.
Conservation agriculture	Reduced C loss; minimum tillage combined with residue retention enhances SOC stability.

5. Carbon sequestration potential of vegetable crops

5.1 Carbon Fixation and Biomass Carbon Stock

Vegetable crops occupy a distinctive niche in the carbon sequestration landscape. While perennial fruit trees and plantation crops store 25-100 times more biomass carbon per unit area than annual field crops, vegetable systems offer advantages of rapid turnover, high planting density and year-round cultivation. The above-ground carbon sequestration potential of vegetable crops ranges from 0.6 to 0.9 Mg C ha⁻¹ yr⁻¹, compared with 2.4-2.8 Mg C ha⁻¹ yr⁻¹ for fruit crops and 3.0-4.2 Mg C ha⁻¹ yr⁻¹ for plantation crops. The photosynthetic pathway strongly influences carbon fixation efficiency. C₄ crops (e.g., maize, sorghum, onion) fix carbon more efficiently than C₃ crops (e.g., tomato, brinjal, cucurbits) due to the CO₂-concentrating mechanism

of the C₄ cycle mediated by phosphoenolpyruvate (PEP) carboxylase. Among vegetable crops studied by Li *et al.* (2019), the carbon sequestration capacity at peak photosynthesis (10:00 h) ranked: corn > sorghum > wheat > tomato > cucumber > cabbage > celery > eggplant > pepper. A critical determinant of per-hectare carbon sequestration is plant density. Naikwadi *et al.* (2024) demonstrated that onion cultivated at very close spacing (15 × 15 cm) achieved the highest carbon sequestration of 3,095.99 kg CO₂ ha⁻¹, while bitter gourd planted at wider spacing recorded only 91.79 kg CO₂ ha⁻¹. This finding establishes planting density as a primary agronomic lever for optimizing carbon sequestration in vegetable systems. Table 5 presents crop-wise carbon content and CO₂ sequestration data from this landmark study ^[31, 35].

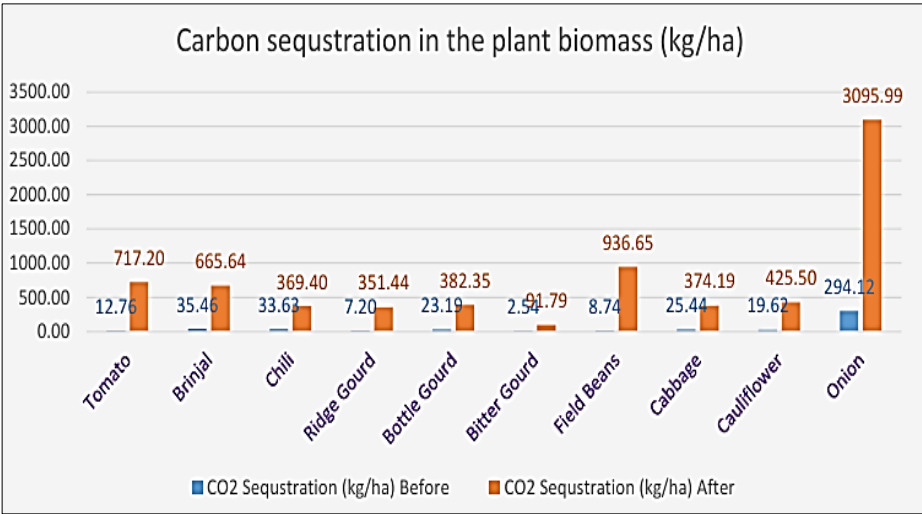


Fig 11: Measurement of total carbon sequestration through the plant biomass

Table 5: Carbon Content and CO₂ Sequestration Potential of Ten Vegetable and Field Crops at Harvest

Crop	Botanical Name	Family	Type	C Content Before (kg ha ⁻¹)	C Content After (kg ha ⁻¹)	CO ₂ Seq. Before (kg ha ⁻¹)	CO ₂ Seq. After (kg ha ⁻¹)
Tomato	<i>Solanum lycopersicum L.</i>	Solanaceae	C ₃	3.479	195.62	12.76	717.20
Brinjal	<i>Solanum melongena</i>	Solanaceae	C ₃	9.671	181.56	35.46	665.64
Chili	<i>Capsicum annuum</i>	Solanaceae	C ₃	9.173	100.75	33.63	369.40
Ridge Gourd	<i>Luffa acutangula L.</i>	Cucurbitaceae	C ₃	1.963	95.86	7.20	351.44
Bottle Gourd	<i>Lagenaria siceraria</i>	Cucurbitaceae	C ₃	6.326	104.29	23.19	382.35
Bitter Gourd	<i>Momordica charantia</i>	Cucurbitaceae	C ₃	0.693	25.04	2.54	91.79
Field Beans	<i>Vicia faba</i>	Fabaceae	C ₃	2.384	255.47	8.74	936.65
Cabbage	<i>Brassica oleracea</i>	Brassicaceae	C ₃	6.940	102.06	25.44	374.19
Cauliflower	<i>Brassica oleracea</i>	Brassicaceae	C ₃	5.353	116.06	19.62	425.50
Onion	<i>Allium cepa</i>	Amaryllidaceae	C ₄	80.222	844.44	294.12	3095.99

5.2 Carbon Stock in Common Garden Vegetables

Ahmed *et al.* (2024) ^[2] used CHN elemental analysis to quantify carbon content in the edible biomass of three common vegetables collected from West Bengal, India. The study revealed that potato (*Solanum tuberosum*) stored the highest carbon at 48.23% on a dry weight basis, followed by

cauliflower (44.90%) and brinjal (43.03%). Total carbon stock per unit area was strongly correlated with edible biomass production, confirming that biomass is the primary determinant of carbon storage potential. Table 6 presents species-wise carbon stock data.

Table 6: Species-wise Carbon Content and Carbon Stock of Selected Vegetables

Vegetable Species	No. per m ²	Mean Weight (g)	Total Biomass (kg m ⁻²)	Carbon (%)	Carbon Stock (kg m ⁻²)
Cauliflower (<i>Brassica oleracea</i>)	4	320	1.280	44.90 ± 1.60	0.57
Brinjal (<i>Solanum melongena</i>)	7	145	1.015	43.03 ± 1.45	0.44
Potato (<i>Solanum tuberosum</i>)	17	93	1.581	48.23 ± 1.67	0.76

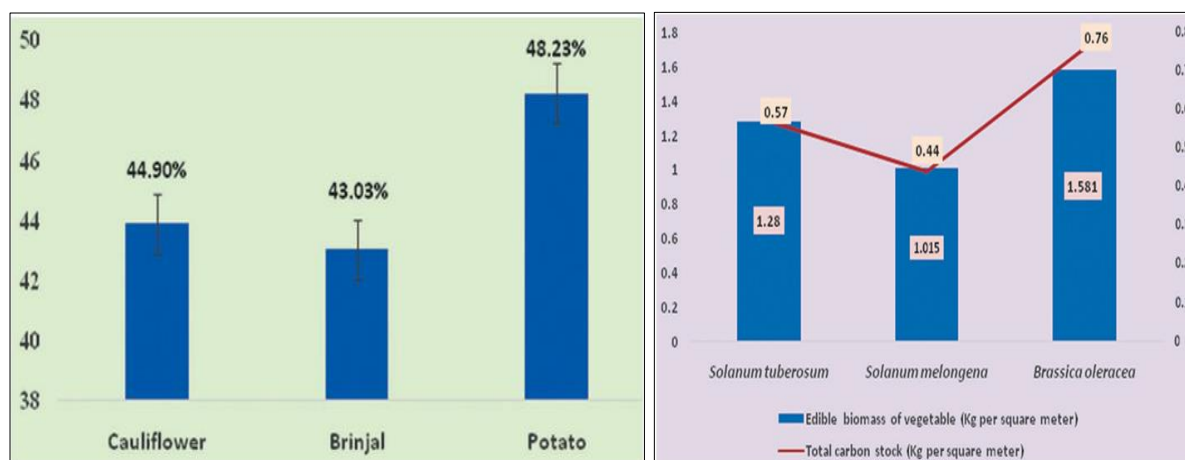


Fig 12 & 13. Mean carbon percentage with SD of the selected vegetables and Inter-relationship between the edible biomass of the selected vegetables and the total carbon stock

5.3 Horticulture-Based Agroforestry Systems

Agroforestry systems incorporating vegetable crops under fruit trees or plantation crops exhibit markedly higher carbon sequestration potential than monoculture vegetable systems. Parmar *et al.* (2021) evaluated 72 horticulture-based agroforestry farms across South Gujarat and reported above-ground tree carbon sequestration ranging from 6.25 to 35,763 kg ha⁻¹. The combination of Mango + *Amorophallus* + *Dioscorea* + Turmeric achieved the maximum carbon sequestration of 35,763 kg ha⁻¹ in Navsari district. The high variability was attributed to species diversity, tree age, plant density and management practices. Trees serve as the primary carbon reservoirs in such systems, with harvestable rotation cycles ranging from 4-5 years for short-rotation species to 45-50 years for long-rotation species such as mango, custard apple and sapota.

6. Organic vegetable farming and carbon sequestration

6.1 Comparative Carbon Sequestration in Organic vs. Conventional Systems

Organic farming systems have consistently demonstrated superior soil carbon sequestration compared with conventional systems. A global meta-analysis by Gattinger *et al.* (2012) involving 14 years of comparative data reported that SOC in the upper 20 cm of soil was 3.50 ± 1.08 Mg C ha⁻¹ higher in organic systems than in non-organic systems. Sardiana (2021), in a study conducted in Bali, Indonesia, found that organic vegetable farming increased SOC sequestration by 1.18 Mg ha⁻¹ yr⁻¹ compared with conventional systems at a 10 cm depth. Organic farming produced 49.02% more labile carbon ($p < 0.01$) and stored 24.52% more total soil carbon. Table 7 presents key comparative data ^[39, 17, 43].

Table 7: Comparison of Soil Carbon Sequestration between Organic and Conventional Vegetable Farming Systems

Farming System	BD (g cm ⁻³)	SOC (%)	Labile C (mg C g ⁻¹)	SOCS (Mg ha ⁻¹)	Remarks
Organic Farming	0.93	3.05	0.72	28.365	1.18 Mg ha ⁻¹ yr ⁻¹ higher than conventional
Conventional Farming	1.03	2.18	0.52	22.454	—
Significance	ns	*	**	*	—

Note: **, * and ns denote significance at 1%, 5% and non-significant levels, respectively. BD = bulk density; SOC = soil organic carbon; SOCS = soil organic carbon sequestration.

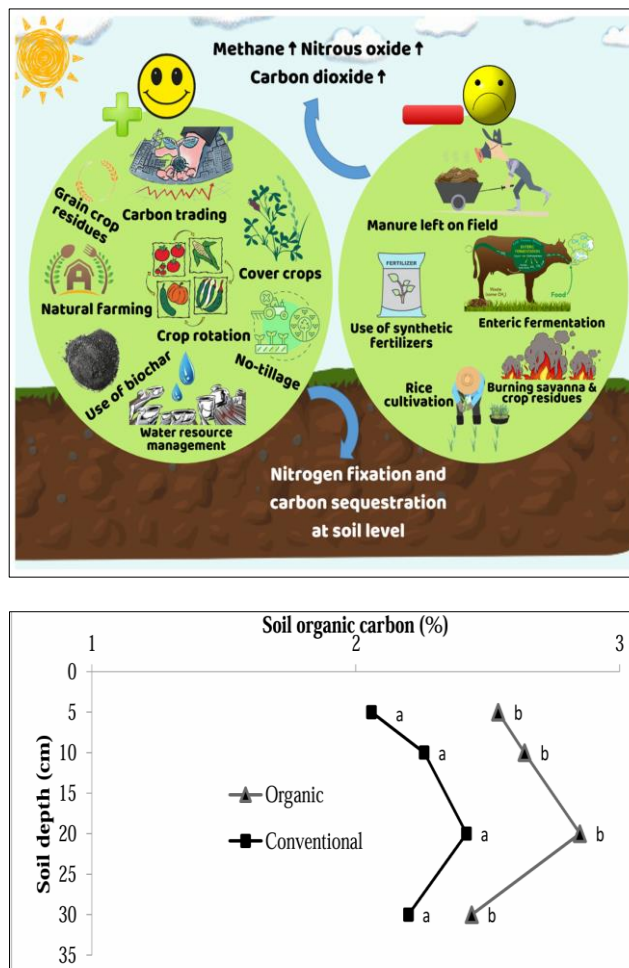


Fig 14 & 15: The influence of carbon farming recommended management practices compared to the main agricultural pollutants and Comparison of soil carbon content profile between conventional and organic vegetable fields in the top 30 cm soil depth.

6.2 GHG Emission Reduction in Organic Vegetable Systems

Beyond direct SOC accumulation, organic vegetable farming reduces overall GHG emissions. Kustermann and Hulsbergen (2008) reported that organic farming uses 2.75 times less energy per hectare than conventional systems. Emission comparisons revealed: N₂O emissions of 852 vs. 1,307 kg CO₂ eq ha⁻¹; CO₂ emissions of 349 vs. 707 kg CO₂ eq ha⁻¹; and an additional carbon sequestration benefit of +110 kg C ha⁻¹ yr⁻¹, reducing greenhouse potential by 415 kg CO₂ eq ha⁻¹ yr⁻¹ in organic systems. Life Cycle Assessment studies indicate that organic tomato production emits 15-31% fewer GHGs than conventional tomato (Fritsche and Eberle, 2007), while organically grown leek generates only 33% of the GHG emissions from conventional production (De Backer *et al.*, 2009).

6.3 Role of Biofertilizers and Biostimulants

Sustainable alternatives to synthetic inputs, particularly plant growth-promoting rhizobacteria (PGPR) and arbuscular mycorrhizal fungi (AMF), significantly enhance soil microbial activity, root exudation and SOC accumulation. AMF improve plant nutrient acquisition, particularly phosphorus, and stimulate the production of glomalin, a glycoprotein that stabilizes soil aggregates and physically protects SOC from decomposition. Biofertilizers additionally contribute to biological nitrogen fixation (BNF) and phosphorus solubilization, reducing synthetic N₂O-emitting fertilizer requirements while improving soil organic matter quality (Dasgan *et al.*, 2023). Legume inclusion in vegetable rotations significantly augments SOC through high-quality nitrogen-rich residues with narrow C:N ratios that promote humification (Lüscher *et al.*, 2014) [16, 11, 10, 34].

7. Role of biochar in soil carbon sequestration

7.1 Biochar Properties and Carbon Stability

Biochar is a carbon-rich, porous material produced by pyrolysis of organic biomass (crop residues, wood, animal manure) under oxygen-limited conditions at temperatures of 300-700°C. Its highly condensed aromatic ring structure renders it recalcitrant to microbial decomposition, with mean residence times of decades to millennia in soil (Lehmann *et al.*, 2015) [30]. This stability distinguishes

biochar from fresh crop residues, where 60-70% of carbon is respired as CO₂ within one year of incorporation. Biochar application mitigates GHG emissions through multiple pathways: improvement of soil aeration reduces methanogenesis; adsorption of ammonium (NH₄⁺) and nitrate (NO₃⁻) decreases nitrification and denitrification, thereby reducing N₂O emissions; and reduced synthetic fertilizer requirements diminish indirect N₂O emissions from fertilizer manufacture and application.

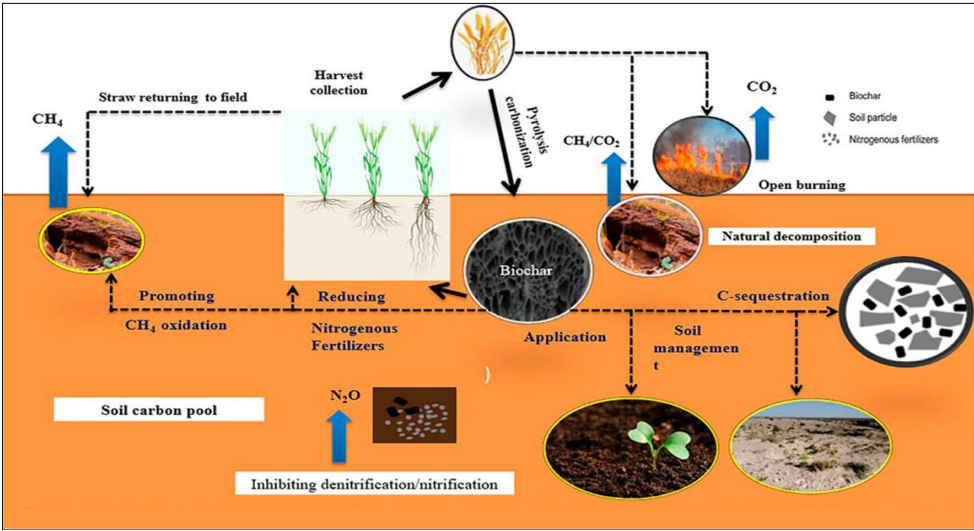


Fig 16: Mechanism of greenhouse gas reduction and soil carbon sequestration through biochar application

Zhang *et al.* (2022) [49] conducted a landmark 3-year biochar experiment under intensive vegetable rotation in Shanghai, China, applying wheat straw biochar at 0 (CK), 10 (C10), 20

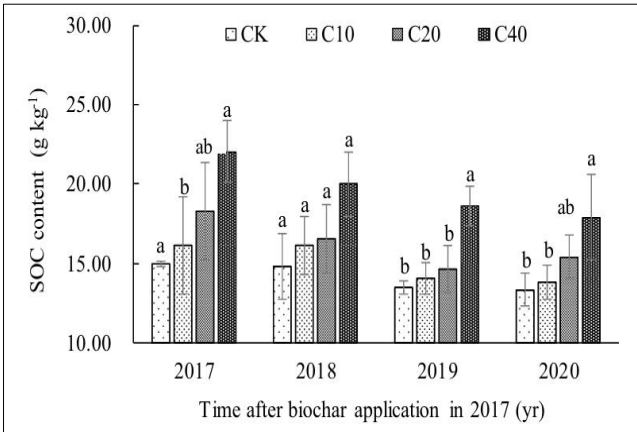
(C20) and 40 (C40) Mg ha⁻¹. Key findings from this study are presented in Table 8.

Table 8: Effect of Straw Biochar Doses on SOC and Labile Carbon Fractions in a 3-Year Vegetable Rotation System

Treatment	SOC (g kg ⁻¹) 2017→2020	SOC Increase vs CK	DOC (mg kg ⁻¹) 2017→2020	DOC/SOC (%)	EOC (g kg ⁻¹)	EOC/SOC (%)
CK (Control)	14.4 → 13.2	—	140.1 → 84.0	9.6 → 6.5	0.230 → 0.238	0.016 → 0.018
C10 (10 Mg ha ⁻¹)	16.1 → 13.8	+8.5-47.5%	111.4 → 72.4	7.2 → 5.4	0.238 → 0.252	0.015 → 0.018
C20 (20 Mg ha ⁻¹)	18.3 → 15.4	+8.0-38.9%	110.4 → 70.2	6.3 → 5.0	0.280 → 0.258	0.016 → 0.017
C40 (40 Mg ha ⁻¹)	22.0 → 17.9	+4.2-35.8%	105.0 → 61.5	4.9 → 4.1	0.320 → 0.279	0.015 → 0.016

Biochar application at 40 Mg ha⁻¹ increased SOC by 4.2-35.8% over control during the three-year period. The increase in large macro-aggregate (> 2000 μm) SOC was the most pronounced (99.7-642.3%), demonstrating that biochar strengthens physical protection of organic carbon. The DOC/SOC and EOC/SOC ratios were reduced in biochar

treatments, indicating greater SOC stability. Lee *et al.* (2025) [29] further reported simultaneous enhancement of carbon sequestration and productivity in radish (*Raphanus raphanistrum*) cultivation under high biochar doses, confirming its dual agronomic and climate benefit.



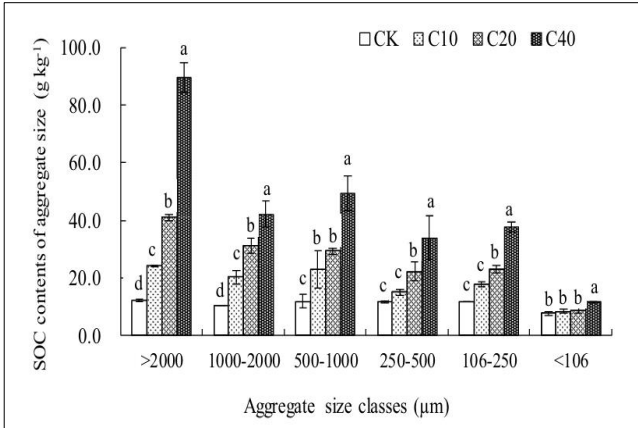


Fig 17 & 18: The SOC contents of different treatments and the soil organic carbon (SOC) contents of different aggregate size classes in year 2020

8. Key research findings-a comparative review

A comprehensive synthesis of experimental studies on carbon sequestration in vegetable cropping systems reveals consistent patterns across crop types, management systems and geographic regions. Carbon sequestration in vegetable crops is influenced by photosynthetic pathway (C₃ vs. C₄), biomass production, plant density, residue management, organic input quality and tillage regime.

8.1 Carbon Sequestration Enzyme Activity

Li *et al.* (2019) [31] established a mechanistic link between photosynthetic enzyme activity and carbon sequestration capacity across nine crops. For C₄ crops, PEP carboxylase activity directly correlated with carbon fixation, while for C₃ crops, RuBP carboxylase (Rubisco) activity was the determining enzyme. Table 9 presents carbon sequestration enzyme activity data for selected crops.

Table 9: Carbon Sequestration Enzyme Activity of Nine Crops

Enzyme Activity (μmol CO ₂ ml ⁻¹ protein min ⁻¹)	Photosynthetic Pathway	PEP Carboxylase	RuBP Carboxylase (Rubisco)
Corn	C ₄	2.856	1.818
Wheat	C ₃	1.794	3.030
Tomato	C ₃	0.725	2.862
Cucumber	C ₃	0.144	2.800
Cabbage	C ₃	1.481	1.556
Celery	C ₃	1.075	2.468
Eggplant	C ₃	0.300	2.062
Pepper	C ₃	0.469	1.518
Sorghum	C ₄	2.425	1.568

Note

- PEP carboxylase activity is considerably higher in C₄ crops (Corn and Sorghum) than in C₃ crops.
- Corn recorded the highest PEP carboxylase activity (2.856 μmol CO₂ ml⁻¹ protein min⁻¹).
- RuBP carboxylase (Rubisco) activity is generally higher in C₃ crops, with Wheat recording the highest value (3.030 μmol CO₂ ml⁻¹ protein min⁻¹).

The results confirm that C₄ crops possess inherently superior carbon fixation capacity due to the CO₂-concentrating PEP mechanism, which suppresses photorespiration. Among C₃ vegetable crops, tomato and cucumber showed the highest Rubisco activity and corresponding carbon sequestration rates, while eggplant and pepper exhibited the lowest values.

8.2 Integrated Nutrient Management in Cauliflower

Kashyap *et al.* (2017) [24] evaluated INM treatments (100% RDF, partial RDF with vermicompost) on SOC stock and sequestration rate in cauliflower at Raipur, India. The 100% RDF treatment recorded the highest SOC stock (12.81 t ha⁻¹) and SOC sequestration rate (0.85 t ha⁻¹ yr⁻¹). A significant linear relationship was established between SOC stock and crop yield (R² = 0.292) and between organic carbon percentage and carbon sequestration rate (R² = 0.449). These findings affirm the importance of nutrient

management in simultaneously optimizing yield and carbon storage.

8.3 Organic Waste Amendments in Tomato Cultivation

Rahman (2013) [40] demonstrated that application of household waste (HW) compost at 3 kg m⁻² achieved the highest organic carbon sequestration of 2.90 Mg ha⁻¹ in tomato cultivation in Bangladesh, with an OC sequestration efficiency of 44.29% of added OC. Chicken manure and cow dung at 4 kg m⁻² were also effective, confirming that diverse organic waste streams can serve as carbon-enriching soil amendments in vegetable systems.

8.4 Cover Crops and Legumes in Vegetable Rotations

Adewale *et al.* (2016) quantified the impact of cover crops on SOC and GHG emissions, finding that SOC loss was reduced from 498 to 57 kg C ha⁻¹ yr⁻¹ with cover crop inclusion, representing a reduction in CO₂-equivalent losses from 1,826 to 209 kg ha⁻¹ yr⁻¹. Cover crops reduced total soil GHG emissions by 41%. Legume incorporation further improved soil quality and increased SOC through high-quality nitrogen-rich residues. Table 10 provides a comparative summary of major research studies on carbon sequestration in vegetable and horticultural cropping systems.

Table 10: Comparative Summary of Research Studies on Carbon Sequestration in Vegetable Cropping Systems

Study	Crop	Location	Treatments / Methodology	Key Findings
Kashyap <i>et al.</i> (2017) ^[24]	Cauliflower	Raipur, India	Integrated Nutrient Management (INM): 100% RDF and organic nutrient combinations	Maximum SOC stock (12.81 t ha ⁻¹) and carbon sequestration rate (0.85 t ha ⁻¹ yr ⁻¹) were recorded under 100% RDF. A significant positive relationship existed between SOC and yield (R ² = 0.292).
Naikwadi <i>et al.</i> (2024) ^[35]	Tomato	Maharashtra, India	Plant biomass carbon estimation using the loss-on-ignition method	Carbon sequestration varied among crops depending mainly on plant density.
	Brinjal			Moderate carbon sequestration potential.
	Onion			Highest CO ₂ sequestration (3095.99 kg ha ⁻¹).
	Field bean			Moderate carbon sequestration.
	Cabbage			Moderate carbon sequestration.
	Cauliflower			Moderate carbon sequestration.
	Gourds			Variable carbon sequestration among species.
	Chilli			Moderate carbon sequestration.
	Bitter gourd			Lowest CO ₂ sequestration (91.79 kg ha ⁻¹).
Sardiana (2021) ^[43]	Carrot	Bali, Indonesia	Organic versus conventional vegetable farming	Organic farming recorded higher SOC (3.05%), SOC stock (28.365 Mg ha ⁻¹) and 49% greater labile carbon than conventional farming.
Ahmed <i>et al.</i> (2024) ^[2]	Potato	West Bengal, India	CHN elemental analyser	Highest carbon content (48.23%) and total carbon stock (0.76 kg m ⁻²).
	Brinjal			Carbon content: 43.03%.
	Cauliflower			Carbon content: 44.90%.
Li <i>et al.</i> (2019) ^[31]	Corn	Beijing, China	GXH-3051 portable CO ₂ infrared analyser and LI-6400 photosynthesis system	Highest PEP carboxylase activity among all crops; superior carbon fixation in C ₄ plants.
	Sorghum			Second highest PEP carboxylase activity among C ₄ crops.
	Wheat			Highest RuBP carboxylase activity among C ₃ crops.
	Tomato			Carbon fixation through the C ₃ pathway.
	Cucumber			Lower PEP activity typical of C ₃ plants.
	Cabbage			C ₃ photosynthetic behaviour.
	Celery			Moderate RuBP carboxylase activity.
	Eggplant			C ₃ photosynthetic characteristics.
	Pepper			C ₃ photosynthetic characteristics.
Zhang <i>et al.</i> (2022) ^[49]	Vegetable rotation system (7 crops)	Shanghai, China	Straw biochar at 0, 10, 20 and 40 Mg ha ⁻¹	Biochar increased SOC by 4.2-35.8% over the control and enhanced macro-aggregate SOC by up to 642%.
Rahman (2013) ^[40]	Tomato	Bangladesh	Household waste, chicken manure and cow dung at 2, 3 and 4 kg m ⁻²	Maximum organic carbon sequestration (2.90 Mg ha ⁻¹) was obtained with household waste at 3 kg m ⁻² ; sequestration efficiency was 44.29%.
Rashid <i>et al.</i> (2025) ^[41]	Spinach (<i>Spinacia oleracea</i>)	Faisalabad, Pakistan	Poultry manure, cow dung and press mud at 1% and 2%	Organic matter increased from 1.21 to 2.23%, while SOC increased from 0.63 to 1.00%.
Parmar <i>et al.</i> (2021) ^[39]	Mango + <i>Amorphophallus</i> + <i>Dioscorea</i> + Turmeric (agroforestry system)	South Gujarat, India	DBH, tree height, stem volume, wood density and carbon estimation	Maximum carbon sequestration (35,763 kg ha ⁻¹) was recorded under the mango-based agroforestry system.

9. Carbon markets and policy frameworks

Carbon markets provide economic incentives for agricultural carbon sequestration by enabling the trading of carbon credits, each credit representing the sequestration or avoidance of one tonne of CO₂ equivalent. Two principal types of carbon markets operate globally: (i) compliance markets, established by national or international regulatory frameworks such as the EU Emissions Trading Scheme (ETS) launched in 2005 and (ii) voluntary carbon markets, where entities purchase credits on a discretionary basis to meet sustainability targets.

China launched the world's largest ETS in 2021, covering approximately one-seventh of global fossil fuel CO₂ emissions. The Clean Development Mechanism (CDM), adopted under the Kyoto Protocol in 1997, remains an important international compliance instrument enabling emission reduction projects in developing countries.

Developing nations collectively require up to US \$6 trillion by 2030 to finance their climate action goals - less than half of which is currently funded - making agricultural carbon markets a critical financing mechanism.

Agricultural soil carbon sequestration is explicitly recognized under UNFCCC, FAO climate-smart agriculture frameworks and the Paris Agreement's Article 6.2 cooperative mechanisms, creating pathways for vegetable producers to access carbon finance. 4 per 1000 Initiative, launched by France in 2015, proposes increasing global SOC stocks by 0.4% per year as a practical target to sequester approximately 1 Gt C yr⁻¹, equivalent to a 50% offset of annual fossil fuel emissions. Integrating vegetable cropping systems into verified carbon sequestration programs represents a practical pathway for smallholder farmers to access carbon finance while improving soil health and agricultural resilience.

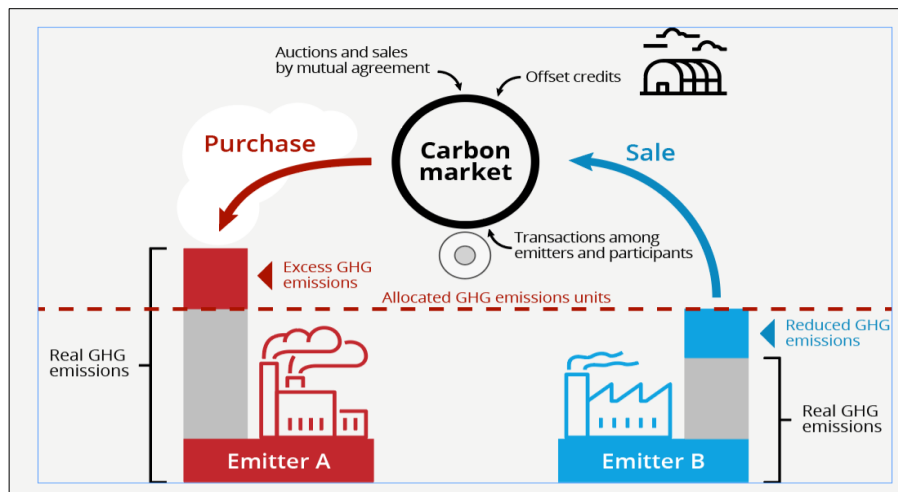


Fig 19: Carbon market

10. Benefits and challenges of carbon sequestration in vegetable systems

10.1 Benefits

Carbon sequestration in vegetable cropping systems delivers multiple co-benefits spanning climate, soil and economic dimensions:

- **Climate Mitigation:** Direct removal of CO₂ from the atmosphere and reduction of net GHG emissions from vegetable production.
- **Soil Health Improvement:** Elevated SOC improves soil structure, water-holding capacity (a 1% increase in SOC can enhance soil water capacity by up to 20,000 gallons per acre), cation exchange capacity and beneficial microbial diversity.
- **Yield Enhancement:** Strong linear relationships between SOC stock and crop yield ($R^2 = 0.292$; Kashyap *et al.*, 2017) confirm that carbon sequestration is synergistic with productivity goals.
- **Biodiversity Conservation:** Organic systems with higher SOC support greater soil fauna and flora diversity, contributing to ecosystem resilience.
- **Economic Value:** Carbon credits, carbon market income and reduced input costs in organic systems provide additional revenue streams for vegetable growers.
- **Improved Water Quality:** Higher SOC reduces surface runoff and nutrient leaching, improving downstream water quality.

10.2 Challenges

Despite its considerable potential, carbon sequestration in vegetable systems faces several scientific, practical and economic challenges:

- **Non-Permanence:** Carbon stored in soil is vulnerable to remobilization through tillage, drought or land-use change. Short-lived vegetable systems with frequent soil disturbance present permanence risks.
- **Saturation:** Soils have a finite carbon sequestration capacity; once saturation is reached, additional organic inputs do not increase SOC stocks, limiting long-term sequestration potential.
- **Measurement and Verification:** Accurate quantification of SOC changes at field and landscape scales requires standardized protocols, advanced instrumentation (e.g., CHN analysers, loss-on-ignition,

Walkley-Black method) and repeated monitoring which is resource-intensive.

- **Additionality:** Demonstrating that sequestration is additional to what would have occurred without intervention is a prerequisite for carbon credit issuance, requiring robust baselines.
- **Variability:** Large spatial and temporal variability in SOC sequestration rates depending on soil type, climate, crop species and management complicates reliable prediction and upscaling.
- **Adoption Barriers:** High initial investment for organic transition, biochar production and conservation tillage equipment limits farmer uptake, particularly in resource-constrained developing regions.
- **Policy Gaps:** Lack of crop-specific carbon sequestration protocols for vegetable crops within existing verification standards (Verified Carbon Standard, Gold Standard) limits market access for vegetable farmers.

11. Future directions

The integration of vegetable crops into climate-smart agriculture frameworks presents a rich frontier for research and policy innovation. Key priority areas include:

- (i) Identification and breeding of vegetable genotypes with high biomass production, deep rooting systems and elevated carbon content to maximize per-hectare sequestration potential;
- (ii) Development of species-specific SOC monitoring protocols and digital soil carbon mapping tools using remote sensing and machine learning;
- (iii) Optimization of biochar production parameters feedstock, pyrolysis temperature, particle size for maximum co-benefits in specific vegetable production systems;
- (iv) Exploration of integrated crop-livestock-microorganism management systems that combine carbon inputs from manure, biochar and cover crops to synergistically build SOC;
- (v) Quantification of carbon sequestration potential of urban and peri-urban vegetable gardens, which represent a rapidly growing sector with significant but unquantified climate relevance; and
- (vi) Development of standardized, crop-type-specific carbon credit protocols for vegetable systems to facilitate farmer participation in voluntary carbon markets.

Long-term field experiments (>10 years) specifically designed for vegetable cropping systems, using multiple sequestration quantification methodologies and spanning

diverse agroclimatic zones, are urgently needed to generate reliable data for policy and practice.

12. Conclusion

Vegetable cropping systems represent a significant but chronically under-quantified component of the agricultural carbon budget. Through photosynthetic carbon fixation, root-mediated SOC formation and organic residue incorporation, vegetable crops function as recurrent, short-term carbon sinks that cumulatively contribute to terrestrial carbon storage. Management practices including organic farming, biochar application, conservation tillage, cover cropping and integrated nutrient management substantially amplify the inherent carbon sequestration potential of vegetable systems, with quantified increases in SOC sequestration of 1.18-5.48 Mg C ha⁻¹ yr⁻¹ under optimized practices.

The evidence synthesized in this review demonstrates that vegetable carbon sequestration is not merely a by-product of production but a manageable, optimizable ecosystem service. The dual benefits of climate mitigation and soil fertility improvement make carbon-sequestration-enhancing practices economically rational for vegetable producers, particularly in an era of expanding carbon markets and climate finance mechanisms.

Realizing the full potential of vegetable crops as carbon sinks requires coordinated action across research, extension and policy domains. Standardized monitoring protocols, genotype-specific characterization, farmer-friendly economic incentives and integration into national climate action plans are essential next steps. Vegetable cropping systems, when managed with carbon intelligence, can meaningfully contribute to global decarbonization goals while ensuring sustainable food security for a growing world population.

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