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UNDERSTANDING CARBON SEQUESTRATION IN FRUIT TREES: FROM MECHANISMS TO CARBON POOL DYNAMICS AND INFLUENCING FACTORS

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ABSTRACT

Carbon sequestration in fruit tree systems can be considered one of the nature-based solutions to mitigate climate change and maintain agricultural production. This review provides a brief summary of the current knowledge about mechanisms of carbon sequestration in fruit trees, carbon dynamics in different carbon pools, and determinants that affect the process of carbon sequestration. Carbon sequestration begins with photosynthesis, when atmospheric CO_2 is incorporated in biomass and distributed to aerial parts and roots. Both these plant compartments participate in forming biomass carbon, litter carbon, and soil organic carbon pools that interact with each other due to litter fall, decomposition, and root turnover. Sizes and stabilities of the mentioned carbon pools can be can be determined by environmental conditions, tree species, orchard management, and soil properties. Climate, age of the fruit trees, density of planting, and intercropping have a strong impact on carbon sequestration capacity.
Keywords **:** biomass, carbon, sequestration, fruit tree, ecosystem.

Introduction

The global population is projected to reach approximately 9.1 billion by the year 2050. With increasing anthropogenic emissions from fossil fuel combustion, industrial activities, and land-use change, atmospheric CO_2 levels have risen significantly, intensifying global warming and associated environmental impacts such as extreme weather events, sea-level rise, and ecosystem degradation (IPCC, 2021). According to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013-2014), the combined global land and ocean surface temperature increased by an average of 0.85^0C between 1880 and 2012, with an estimated range of 0.65^0C to 1.06^0C (Wolf *et al.*, 2017). A special report by IPCC that the increase in global mean temperature has impacted people, ecosystems and livelihoods across the world. Fruit cultivation is regarded as a potential component of good agricultural practices; however, its effectiveness may be adversely affected by the impacts of climate change (Rana and Rana, 2023; Jhalegar *et al.*, 2012). The integration of trees, often arranged in diverse systems, enhances overall productivity, facilitates efficient nutrient cycling and contributes to the maintenance of ecological balance due to their significant carbon sequestration potential (Rana *et al.*, 2020; Kumar *et al.*, 2021; Rai *et al.*, 2021; Sheikh *et al.*, 2021; Tamang *et al.*, 2021).

Methodology

A systematic approach was adopted to conduct this review. Using a combination of keywords associated with the study issue, extensive searches of electronic databases including Google Scholar, Scopus were conducted to find pertinent literature. Peer-reviewed books, journals and conference papers published during a given time period were chosen using predetermined inclusion criteria. The selection of articles comprised of the initial selection of titles and the abstracts of relevant research papers, after which the full articles were evaluated to check their relevance and quality. Relevant data were collected and sorted based on thematic analysis. This structured methodology ensured the reliability, transparency and reproducibility of the review findings.

Fruit trees and carbon sequestration

Fruit-based systems are increasingly recognized as a viable and sustainable alternative for enhancing carbon sequestration in terrestrial ecosystems Through photosynthesis, trees, plants, and crops absorb carbon dioxide, which is then stored as carbon in biomass found in tree trunks, branches, foliage, roots, and soils (EPA, 2008). A study conducted in 2022 at the Purwodadi Botanical Garden in Indonesia aimed at determining the carbon storing capacity of different collections of fruit varieties revealed that most of the indigenous fruit trees are carbon sinks and should be encouraged in restoration activities to combat climate change (Yulistyarini & Hadiah, 2022). A study conducted in Mizoram, Northeast India, to evaluate the growth performance, carbon stock, and sequestration potential of oil palm plantations reported substantial carbon storage in these systems, with values exceeding those observed in shifting cultivation (Singh *et al*., 2018). "Likewise, a study carried out in 2021 in the Sargodha district of Pakistan assessed the contribution of citrus orchards to climate change mitigation through carbon sequestration. The findings indicated that the application of simple and practical carbon measurement techniques can produce reliable estimates, thereby encouraging greater participation of developing countries in incentive-based mechanisms such as REDD+" (Yasin *et al*., 2021).

Mechanism of Carbon capture in fruit trees

Fruit based production systems operate as a self-sustaining systems in which solar energy is efficiently utilized across multiple vertical layers, enabling optimal exploitation of soil resources and enhanced cropping intensity. Such systems are basically assembled into three principal components-namely, main crop, filler crop and intercrops which occupy distinct spatial tiers within the production framework (Upadhyaya *et al*., 1999). Carbon capture and storage in fruit trees occurs through its accumulation in various plant parts, including trunks, branches, leaves, flowers, fruits and roots. "According to Schaffer *et al*., (1999), exposure of tropical and subtropical fruit crops such as avocado, banana, mangosteen, citrus and mango to elevated CO_2 concentrations significantly enhances photosynthetic activity, leading to increased biomass production." Studies have shown that the photosynthetic activity of mangosteen could be increased by 40-60% due to exposure to elevated CO_2 at 800 ppm for one year compared to normal environmental conditions. Moreover, the abundance of flowers and specific features of these trees make them highly efficient in carbon dioxide assimilation and storage within their structures like cellulose (Bickford, 2007). In this regard, fruit tree gardens have significant potential to facilitate sustainable development amidst climate change in tropical regions, especially considering the increasing agricultural activity and socioeconomic problems leading to depletion of forest (FAO, 2010). The carbon sequestration carried out by fruit trees, particularly under horticultural orchard systems, occurs through several biological and ecological activities that relate to the processes of photosynthesis and formation of plant biomass. Carbon capture in fruit trees is achieved via carbon dioxide uptake from the environment through leaf stomata, followed by its conversion into carbohydrates through photosynthesis. The produced carbohydrates will be used for creating different plant parts, such as leaves, stalks, branches, and roots leading to increased carbon sequestration in upper part of the soil. In contrast, there is ample carbon contained underground because of root proliferation, root exudation and activities of soil microorganisms. Carbon sequestration in orchard ecosystems becomes much more possible due to litter fall aided by biological processes, in which leaves, pruned materials and dead roots play significant roles. The decomposition of these organic compounds contribute to increasing the amount of organics in soil, making it possible to stabilize carbon in humified form. Moreover, the use of fruit trees in the agroforestry approach makes the ecosystem resourceful because sunlight, water, and other useful resources will be used more efficiently, making it possible to increase biomass and consequently enhancing carbon sequestration in comparison with monoculture farming methods. In addition, carbon can be stored within the long-lived woody parts of plants or even utilized in durable products, which results in longer carbon storage out of the atmosphere. Overall, carbon sequestration in fruit trees is governed by a combination of processes, including atmospheric CO_2 fixation, biomass development, litter decomposition, and soil carbon stabilization, highlighting the important role of fruit-based systems as effective and sustainable carbon sinks.

Carbon Pools in Fruit Tree Systems

Above and belowground biomass

"A study done in Indonesia estimated that the carbon sequestration capacity of fruit tree biomass, with average carbon stock values ranging from 382 Gg to 245,726 Gg" (Gunamantha *et al*., 2011). Mango orchard system have a carbon sequestration rate of 0.59 tonnes per hectare per year with CO_2 mitigation potential of 2.86 Mg CO_2 e per hectare (Singh *et al*., 2024). Siddesh *et al*. (2025) evaluated the carbon sequestration and net greenhouse gas mitigation potential of different fruit production systems on transformed land. The mango production system reported aboveground biomass stock of 18.56 and belowground biomass stock of 11.6 Mg C per hectare. Elevated atmospheric CO_2 concentrations have been reported to enhance photosynthetic activity in tropical and sub-tropical fruit crops, leading to increased tree biomass and consequently contributing to the reduction of atmospheric carbon dioxide (Pandya *et al*., 2013). “In coffee-based agroforestry systems, the aboveground carbon pool has been found to store a greater proportion of carbon compared to other carbon components” (Niguse *et al*., 2022). Under Assam condition, mango orchards reported an aboveground carbon pool of 58.759 tonnes per hectare (Ganeshamurthy *et al*., 2019).

Soil carbon

The primary way of carbon being added to the soil is through photosynthesis; however, the CO_2 in the air can be dissolved in the moisture present in the soil in minimal amounts. Therefore, the primary factor affecting carbon sequestration in an ecosystem is net primary productivity, which is the difference between carbon entering the ecosystem through photosynthesis and that exiting the ecosystem through respiration. The soil carbon pool constitutes one of the largest and most dynamic pools of carbon on Earth and serves as a critically important link in the global carbon cycle and climate regulation, comprising soil organic carbon and soil inorganic carbon. “SOC originates from plant litter, root biomass, microbial residue, and organic amendments, which undergo decomposition and stabilization through complex biochemical processes mediated by soil microorganisms” (Lal, 2004). The carbon content in soil is determined by how the land is utilized, the type of vegetation, and the type of land management practices, for instance, agroforestry and fruit tree-based systems enhances carbon content due to litter fall and root turnover (Nair *et al*., 2010). In addition, intensified land cultivation practices and land degradation contribute to carbon depletion and atmospheric CO_2 concentration (Smith *et al*., 2008). In The distribution of soil particle sizes and the amount of organic carbon in the soil are significantly correlated (Gunamantha *et al*., 2021). In particular, there is a weak and negative correlation between soil organic carbon and the proportions of sand and silt (Dong *et al*., 2017). While clay particles show the largest positive link with soil organic carbon, sandy soils often have low levels of organic carbon (Eusterhues *et al*., 2003). Therefore, improving soil sequestration depends more on efficient soil management techniques like adding manure or agricultural residues than only soil structure (Blanco-Canqui, 2013). “Furthermore, soil depths of 0–25 cm, 0–50 cm, and 0–75 cm have been found to have the strongest positive relationships between clay dispersion and soil organic carbon” (Somasundaram *et al*., 2017).

Litter biomass

Litter biomass represents a crucial intermediate carbon pool in fruit-based production systems, serving as a link between aboveground biomass and soil organic carbon dynamics. According to a study done to assess the carbon sequestration potential of different fruit production systems, litter has a poor biomass accumulation and carbon storage capacity (Singh *et al*., 2024). Litter biomass ultimately contributes to the soil organic carbon pool on decomposition. The decomposition rate of litter and the stabilization of carbon are largely governed by species composition, environmental conditions, and management practices including mulching and residue retention. Evidence suggests that fruit-based systems significantly contribute to soil carbon storage through litter inputs, thereby enhancing soil fertility, improving structural properties, and increasing moisture retention, while also aiding in the reduction of atmospheric CO_2 concentrations (Montagnini & Nair, 2004., Kumar & Nair, 2011). Moreover, effective litter management practices in orchards facilitate nutrient cycling and support sustained productivity, underscoring its importance in the overall carbon balance of horticultural systems (Lal, 2004).

Factors affecting carbon sequestration in fruit trees

Tree Species and Genotype

Fruit trees vary from each other depending on their rate of growth, canopy structure, density of the wood and life span. It is true that slow growing trees can be capable of storing carbon for a long time since their wood is dense, but faster growing trees such as citrus and mango will gain biomass faster (Lal, 2004). Carbon allocation patterns and photosynthetic efficiency are also impacted by genotypic heterogeneity within species (Nair *et al*., 2009).

Age and Growth Stage of Trees

Fruit tree age has a significant impact on carbon sequestration. Mature trees retain more carbon in their woody biomass, whereas young trees develop quickly and accumulate more carbon. But as trees get older, the rate of sequestration usually decreases (Nowak & Crane, 2002). Instead of being active carbon sinks, older orchards might serve as stationary carbon reservoirs.

Biomass Production and Allocation

Carbon storage capacity is determined by the entire biomass that fruit trees produce, which includes both belowground and aboveground components. Woody tissues and root systems retain a substantial amount of carbon (IPCC, 2006). Through root turnover and exudation, carbon allocation to roots also improves carbon storage (Jackson *et al*., 1997).

Soil Properties

Soil characteristics such as texture, structure, pH, and nutrient status play a crucial role in carbon sequestration. Clay-rich soils tend to stabilize more organic carbon compared to sandy soils due to stronger organo-mineral interactions (Six *et al*., 2002). Soil fertility influences plant growth and litter production, thereby affecting carbon inputs into the soil (Lal, 2004).

Climate and Environmental Conditions

Temperature, precipitation, and solar radiation are examples of climate variables that have a direct impact on photosynthesis and biomass production. While harsh circumstances like drought or cold can restrict carbon sequestration, warm temperatures and sufficient rainfall generally improve it (FAO, 2013). Although this effect is dependent on the availability of nutrients, elevated CO_2 levels may potentially improve photosynthetic rates.

Orchard Management Practices

The ability of the trees to store carbon largely depends on the method used in the orchards. This will be facilitated by activities like mulching, intercropping, minimum tillage, and application of organic fertilizer to reduce the loss of carbon and increase in soil organic carbon content (Paustian *et al*., 2016). Growth and biomass can also be regulated using fertilizer and irrigation methods.

Conclusion

Carbon sequestration has come up as an essential natural phenomenon in curbing the increase in atmospheric carbon dioxide levels. In this regard, fruit tree-based systems are significant since they are perennial in nature, and they have the capability of sequestering carbon into different pools. This system incorporates different carbon pools including soil carbon, litter, above ground biomass, and belowground biomass that ensure carbon storage and ecological sustainability in the long run. There are various factors that determine the extent of carbon sequestration in fruit tree systems. Biological parameters such as species, genotype, and age play a vital role in determining carbon distribution and growth rate, while climatic and soil parameters affect productivity and carbon sequestration in the system. Additionally, the application of practices such as pruning, fertilization, irrigation, organic material, and minimum soil disturbance has an impact on carbon sequestration potential. The inclusion of fruit trees in other systems such as agroforestry improves these benefits through increased production and improved soil quality. Optimization of carbon sequestration potential in fruit tree systems requires the application of sustainable management practices and a clear understanding of the carbon pools and influencing factors. Future studies should concentrate on establishing site-specific strategies to optimise sequestration potential and measuring carbon dynamics across various fruit species and agroecological environments. These initiatives will improve soil fertility, productivity and the resilience of fruit-based systems in addition to mitigating the effects of climate change.

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