Available online at
http://currentagriculturetrends.vitalbiotech.org/

ISSN (E): 2583 – 1933

Curr. Agri.Tren.:e- Newsletter, (2025) *4*(7), 19-24

Current Agriculture Trends: *e-Newsletter*

Article ID: 403

Carbon Sequestration Potential of Horticulture Systems

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Article History
Received: 09. 07.2025
Revised: 14. 07.2025
Accepted: 19. 07.2025

INTRODUCTION

As the world becomes increasingly concerned about climate change and its effects on ecosystems, agriculture is no longer being considered for its emissions role alone but also for what it can do to help mitigate climate change. Horticulture, for years considered vital for contributing nutrition, livelihood, and beauty, has another, less discussed aspect providing carbon sequestration through the capture and storage of atmospheric CO_2 in plant biomass and soil.

Horticulture systems, particularly those including perennial fruit tree crops, agroforestry, and urban forestry programs, can largely reduce carbon emissions. Such systems can serve as carbon sinks, which can balance greenhouse gas emissions from other activities while enhancing soil health, water holding capacity, and ecosystem diversity. The capacity of horticultural crops to sequester carbon makes them an integral part of climate-resilient and sustainable agriculture.

Climate change poses one of the greatest challenges of the 21st century, with far-reaching implications for food security, biodiversity, and the stability of global ecosystems. The agricultural sector, while being a victim of changing climate patterns, is also a major contributor to greenhouse gas (GHG) emissions, primarily through land-use change, soil degradation, and the use of synthetic inputs. In response, there is an urgent global need to transition toward climate-smart and environmentally sustainable agricultural practices.

Horticulture cultivation of fruits, vegetables, flowers, medicinal and aromatic plants, and landscape species is usually hailed for its contributions to food, incomes, and beauty. Besides such socio-economic roles, horticulture assumes a central but underemphasized position in the mitigation of climate change, and this is through carbon sequestration.

Carbon sequestration is the capture of atmospheric carbon dioxide (CO_2) and its long-term storage in plant biomass and soil. As compared to annual field crops, many horticultural systems, particularly those with perennial fruit trees, plantation crops, and agroforestry components, can sequester considerable carbon in their woody biomass. Additionally, practices such as mulching, organic amendments, reduced tillage, and cover cropping build up soil organic carbon, and therefore, horticultural soils can be effective carbon sinks. In addition, urban and peri-urban horticulture, such as ornamental trees, green belts, and rooftop gardens, are not only providing CO_2 uptake but also microclimate control and urban energy savings. These systems provide a nature-based solution for the sustainable development objectives (SDGs), especially those connected with climate action (SDG 13), life on land (SDG 15), and sustainable cities (SDG 11). Hence, the inclusion of carbon sequestration in horticultural policy and planning has the added advantage of reducing climate change while, at the same time, improving soil health, biodiversity, and agriculture resilience. Identification and maximization of horticulture's carbon sequestration potential may prove to be a game-changer within the overall context of sustainable land management and climate-smart agriculture.

2. What is Carbon Sequestration?

Carbon sequestration is the natural or industrial process of capturing and storing atmospheric carbon dioxide (CO_2) to avoid or postpone the effects of climate change. It is the process of moving CO_2 from the atmosphere into long-term reservoirs like plants, soil, oceans, and rocks, where it stays stored for decades up to thousands of years. In horticultural ecosystems, carbon is mainly sequestered by two principal processes. Firstly, biomass buildup happens in perennial crops like trees, shrubs, and herbaceous plants.

These crops take up CO_2 during photosynthesis and fix it in their trunks, branches, roots, and leaves. Secondly, soil organic carbon (SOC) accumulation occurs due to deposition and decomposition of plant litter, root exudates, and organic manures like compost and farmyard manure. This accumulation not only traps carbon but also enhances soil structure, fertility, and water-holding capacity, hence serving as a long-term sink for carbon.

3. Contribution of Horticultural Systems to Carbon Sequestration

Horticultural production systems have a special ability to assist with climate change mitigation. Their diversity of organisms, perennial quality, and ability to be integrated into agricultural ecosystems help them retain and trap carbon. Various horticultural practices and crops affect their ability to sequester carbon in various fashions.

3.1. Fruit Orchards

Perennial fruit orchards represent one of the most effective horticultural systems for carbon sequestration because of their long lifetime and repetitive biomass buildup. Trees like mango, guava, citrus, apple, and coconut can sequester and store enormous amounts of carbon in their woody biomass as well as deep root systems.

The use of organic mulches in orchards is useful to stimulate microbial activity and humus formation and improve carbon sequestration in the soil. The intercropping and cover cropping also enhances ground cover and adds soil organic carbon content. For example, a mature mango tree can sequester up to 25–30 kilograms of CO_2 per year. An entire orchard, depending on its age, management practices, and planting density, can sequester several tonnes of CO_2 per hectare annually.

3.2. Agroforestry Systems

Horticultural agroforestry systems combine fruit trees with field crops, vegetables, or fodder grasses. This integration maximizes land use, increases biodiversity, and encourages ecological stability. Such systems produce multi-strata carbon sinks by stacking plant species of varying heights and growth habits vertically. The incorporation of leguminous crops within agroforestry systems also increases soil fertility by nitrogen fixation and encourages additional carbon sequestration in plant biomass and soil. For example, a guava–cowpea–fodder grass agroforestry system has been documented to sequester around 2–4 tonnes of CO_2 per hectare annually. Agroforestry is thus a viable and sustainable climate-smart practice.

3.3. Vegetable Crops

Vegetable crops are generally of short duration, yet their contribution to carbon sequestration cannot be discounted, especially when they are produced with conservation-oriented and sustainable approaches. These approaches contribute to soil organic matter development and lower emissions.

Important practices which increase vegetable soil carbon are the use of organic manure, compost, and vermicompost, which supplement the soil with organic matter. Minimum or zero tillage methods ensure the conservation of soil structure and avoid the degradation of organic carbon. Organic mulch usage minimizes evaporation and soil erosion, also promoting the retention of carbon. Crop rotation and the return of crop residues to the soil also lead to greater biomass input and fertility of the soil. If implemented on a large scale, these practices can collectively sequester large quantities of soil carbon and lower the greenhouse gas emissions from vegetable production systems.

3.4. Ornamental and Urban Horticulture

Urban and peri-urban agriculture contributes more and more to carbon sequestration by bringing and sustaining green cover in built-up areas. Urban greens like parks, botanical gardens, avenue plantations, vertical gardens, and roof gardens act as significant carbon sinks along with providing better air quality and reducing urban heat islands.

Garden trees, shrubs, hedges, and lawns sequester and store atmospheric CO_2, especially if native or long-lived species are cultivated. These green spaces serve to enhance mental health, urban nature diversity, and the control of local microclimates aside from their carbon sequestration capacity. For instance, a properly managed urban park sequesters roughly 5–10 tonnes of CO_2 per hectare annually, depending on plant species mix, planting density, and maintenance regimes.

3.5. Floriculture and Nursery Management

Floriculture and nursery management systems also sequester carbon, though to a lesser extent. Even though each flower plant and sapling is of relatively small biomass, their dense plantings and continuous production cycles exert a cumulative effect on carbon storage.

The regular use of organic potting media like cocopeat, compost, and biochar increases the carbon content of the soil. Not only does this method contribute to carbon sequestration, but it also decreases the reliance on peat excavation, which has been known to put vast amounts of stored carbon into the environment. With time, such small but intensive horticulture systems can contribute significantly to soil organic carbon build-up, especially in peri-urban and institutional environments.

3.6. Protected Horticulture

Protected cultivation systems such as polyhouses and greenhouses, which are widely applied for high-value horticultural production, can similarly be optimized for promoting carbon sequestration and minimizing greenhouse gas emissions.

With the use of organic substrates, cover crops, and biofertilizers, the environmental impact of these systems can be minimized while ensuring productivity. In addition, technologies like solar-powered irrigation systems, sensor-based fertigation systems, and biodegradable mulch materials ensure resource conservation and efficiency. Protected horticulture can play a beneficial role in sequestering soil carbon and energy-saving crop growth if designed and managed on the principles of ecology.

Carbon Sequestration Potential: Crop-wise Estimates

Horticultural System	Estimated Carbon Sequestration Potential (t CO_2 ha^{-1} yr^{-1})
Mango Orchard	5–8
Citrus (Orange/Lemon)	4–6
Guava	3–5
Banana (short cycle)	2–3
Coconut Plantation	6–10
Arecanut Plantation	4–7
Tea and Coffee Plantations	5–9
Flower crops (e.g., rose)	1–2
Multitier Vegetable Systems	2–4
Urban/Peri-urban Horticulture	Variable (0.5–3)

ISSN (E): 2583 – 1933

4. Influencing Factors for Carbon Sequestration in Horticulture

The capacity and the rate of carbon sequestration in horticultural systems are influenced by various factors. They are:

Plant Species and Growth Rate: Varying in capability for carbon sequestration, different horticultural crops are. Woody perennial, deep-rooted, fast-growing species like coconut, guava, and mango are more likely to sequester more carbon both in their biomass and root system than herbaceous or shallow-rooted species.

Management Practices: Farm management is very important. Practices like frequent pruning, clear application of organic amendments (e.g., compost, farmyard manure), proper irrigation, and balanced nutrient input not only promote plant growth but also enhance the return of organic matter to soil, thus enriching soil carbon pools.

Soil Type and Fertility: The chemical and physical properties of the soil have a critical influence on its capacity to store carbon. Clay soils, having a greater surface area and chemical binding affinity, are capable of storing more organic carbon than sandy soils. Likewise, organic matter-rich soils facilitate improved microbial activity and stable long-term carbon.

Climatic Conditions: Climate has a large impact on biomass production. Subtropical and tropical areas with more extensive growing seasons, increased temperatures, and increased sunlight exposure encourage intensive plant growth and increased yearly carbon fixation. But detrimental weather events can equalize these benefits in the event that systems lack resilience.

5. Estimating Carbon Sequestration Potential

It is vital to estimate carbon sequestration in horticultural systems for climate accounting, policy, and access to carbon credits. A number of approaches are generally applied:

Allometric Equations: These are statistical models that project the biomass and carbon content of a tree from measurable characteristics like tree diameter at breast height (DBH), total height, and wood density. They are species-dependent and are commonly applied in orchard and agroforestry estimation.

Remote Sensing and GIS (Geographic Information System): Satellite data and GIS software are useful for mapping vegetation cover, land-use change monitoring, and carbon stock estimation over extensive areas. These technologies provide a cost-saving and scalable method of carbon estimation, particularly in urban and peri-urban horticulture landscapes.

Soil Testing and Laboratory Analysis: Regeneration of soil organic carbon (SOC) is periodically measured to elucidate below-ground carbon processes. Soil samples are taken at various depths and tested for the content of organic carbon to monitor change over time as a result of management interventions. Combined, these techniques give an overall picture of the potential for carbon sequestration and trends in horticultural systems.

6. Benefits Beyond Carbon Sequestration

The contribution of horticulture to climate mitigation goes beyond the mere capture of carbon. It provides considerable agro-ecological as well as socio-economic advantages:

Soil Health: The addition of organic matter from plant residues, mulches, and compost improves soil structure, water-holding capacity, and nutrient cycling. This leads to healthier and more productive soils that sustainably promote crop growth.

Biodiversity Conservation: Horticultural systems, especially those that include agroforestry or mixed cropping, provide multiple habitats for beneficial insects, birds, pollinators, and microorganisms in the soil. All this biodiversity helps in maintaining ecosystem balance and managing pests.

Climate Resilience: Perennial horticultural systems minimize the effects of climate variability through stabilizing microclimates, preventing soil loss due to erosion, and providing green cover year-round. These horticultural systems serve as temperature buffers during extreme temperatures, droughts, and heavy rainfalls.

Improved Livelihoods and Income Streams: Farmers can gain economically through carbon trading system participation and payments for ecosystem services. Also, horticultural crop diversification raises the number of income sources and minimizes crop failure risk, leading to enhanced rural livelihoods.

7. Challenges and Way Forward

Although the potential of horticultural systems in carbon sequestration has been identified, there are various challenges facing their utilization and measurement in addressing climate change mitigation.

Major Challenges

Insufficient Reliable Data and Monitoring Tools: It is not easy to find accurate, long-term datasets and standardized protocols to quantify carbon sequestration particularly in horticultural systems. Models are generally suited for forestry or agronomic crops rather than for diverse and mixed horticultural systems.

Limited Farmer Awareness: Most farmers and horticulturists are unaware of the carbon sequestration potential of their operations and related environmental and economic value. Lacking awareness, the uptake of carbon-smart horticultural practices is low.

Need for Location-Specific Models and Validation Methods: Sequestration rates differ widely with crop species, soil type, climate, and agronomic practices. Hence, models generalized over larger areas fail to capture local differences. There is an urgent need for region- and crop-based tools to facilitate estimation as well as validation accurately.

Way Forward

Horticulture Carbon Credit Program Development: Mechanisms for rewarding carbon sequestration in horticultural landscapes should be developed to specifically acknowledge and reward sequestration activities in horticultural landscapes. Incorporation of horticulture in voluntary and compliance markets for carbon would enable growers to receive financial incentives and assistance.

Integration into Extension and Capacity Building Programs: Extension services and horticultural training modules should be integrated with principles of carbon farming. Demonstrations farms, farmer field schools, and digital platforms can facilitate promoting climate-smart practices at the farm level.

Policy Support and Climate-Resilient Research: National and regional policy needs to give horticulture high priority in climate action plans. Investment in research and development of climate-resilient varieties, organic amendments, and carbon monitoring tools will be important. Policy incentives such as subsidies, recognition schemes, and green certification programs can also be used to support sustainable approaches.

A coordinated and inclusive approach is needed to tap the full climate and ecological value of horticultural systems.

8. CONCLUSION

Horticultural systems, including perennial fruit orchards, agroforestry models, and sustainable vegetables, hold an untapped yet robust carbon sequestration strategy. They capture and sequester atmospheric CO_2 as well as enhance soil health, promote biodiversity, and enhance climate variability resilience.

By bringing climate-smart horticulture practices into the mainstream of agriculture, we can transition to low-carbon, high-resilience agricultural systems. But this will happen only through the concerted efforts of researchers, policymakers, extension agents, and farmers. With enabling policies, strategic research, and greater awareness, horticulture can become a pillar of climate change mitigation and sustainable agriculture development.

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