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Carbon gardens: A nature-based approach for climate change mitigation and sustainable landscapes

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Abstract

Carbon gardens are intentionally designed multifunctional landscapes that integrate trees, shrubs, perennial vegetation, edible crops, and soil-building practices to maximize carbon sequestration while delivering a wide range of ecosystem services. As an emerging nature-based solution, they combine principles of regenerative agriculture, agroforestry, ecological landscaping, and sustainable soil management to capture atmospheric carbon and enhance long-term storage in plant biomass and soil organic carbon pools. This review synthesizes the concept, design principles, carbon sequestration mechanisms, carbon storage potential, environmental benefits, and role of carbon gardens in promoting food security, biodiversity conservation, water conservation, urban climate resilience, and soil health. The article further highlights their application in urban and rural landscapes, their integration with carbon-negative farming through practices such as biochar use, compost recycling, and agroforestry, and discusses key challenges related to carbon measurement, establishment costs, land availability, and long-term management. Emerging advances in remote sensing, carbon accounting, and climate-smart landscape design, together with supportive policies and carbon credit mechanisms, are expected to facilitate wider adoption. Carbon gardens therefore represent a practical, scalable, and resilient approach for mitigating climate change while contributing to sustainable land management, ecosystem restoration, and carbon-negative development.

Keywords: Carbon gardens, carbon sequestration, agroforestry, biochar, biodiversity, soil carbon

1. Introduction

Rising atmospheric carbon dioxide (CO₂) concentrations are the primary driver of anthropogenic climate change, threatening ecosystem stability, agricultural productivity, biodiversity, and human well-being. Limiting global warming to 1.5–2 °C requires rapid greenhouse gas emission reductions together with large-scale carbon dioxide removal (CDR), among which nature-based solutions (NbS) are widely recognized for simultaneously mitigating climate change, restoring ecosystems, conserving biodiversity, and improving soil, water, and human well-being (IUCN, 2020; IPCC, 2023; UNEP, 2024; Buma *et al.*, 2024) [5, 13, 15, 32].

Carbon gardens have emerged as a multifunctional NbS that maximizes long-term carbon sequestration in vegetation and soils while providing ecological, economic, and social benefits. Unlike conventional ornamental landscapes, they integrate regenerative agriculture, agroforestry, ecological landscaping, sustainable horticulture, permaculture, and soil carbon management to enhance carbon capture through perennial vegetation, species diversity, organic matter recycling, minimal soil disturbance, and improved soil biological activity (Lal, 2020; Singh *et al.*, 2024; Khan *et al.*, 2026) [19, 29, 18].

The scientific basis of carbon gardens lies in enhancing photosynthetic carbon fixation and stabilizing carbon in plant biomass and soil organic carbon (SOC) through root turnover, litter decomposition, microbial activity, compost, mulching, biochar, and reduced soil disturbance. Increasing carbon inputs while improving long-term SOC stability is considered essential for effective nature-based climate solutions (Pellegrini *et al.*, 2026) [28].

Beyond carbon sequestration, carbon gardens support biodiversity conservation, pollinator habitats, nutrient cycling, erosion control, water infiltration, urban cooling, climate resilience, food production, and recreation, aligning with global climate adaptation, mitigation, and

ecosystem restoration goals (IPCC, 2022; FAO, 2022; Buma *et al.*, 2024) [5, 14, 8]. Their relevance is further strengthened by growing interest in regenerative agriculture, carbon farming, and urban green infrastructure, where perennial vegetation, agroforestry, cover crops, organic amendments, and ecological landscape design enhance terrestrial carbon storage, soil quality, and ecosystem resilience (Nolan *et al.*, 2021; Singh *et al.*, 2024; Pellegrini *et al.*, 2026) [26, 29, 28]. This review critically synthesizes the current knowledge on the concept, scientific basis, design principles, carbon sequestration potential, ecosystem services, implementation strategies, challenges, and future prospects of carbon gardens as a scalable nature-based solution for climate change mitigation and sustainable landscape management.

2. Concept and Definition of Carbon Gardens

The term carbon garden is an emerging concept in climate-smart landscape management and has not yet been formally defined in the scientific literature. It has evolved from the broader concepts of nature-based solutions (NbS), carbon farming, regenerative agriculture, agroforestry, ecological restoration, and sustainable landscape design, all of which aim to enhance carbon sequestration while delivering multiple ecosystem services (IUCN, 2020; IPCC, 2022; Singh *et al.*, 2024) [29, 13, 14]. Therefore, establishing an operational definition is important for providing conceptual clarity and guiding future research and implementation. For the purpose of this review, a carbon garden is defined as: A deliberately designed and managed landscape that integrates carbon-sequestering vegetation, carbon-conserving soil management practices, and ecological landscape design to maximize long-term carbon storage in plant biomass and soils while simultaneously enhancing biodiversity, ecosystem services, climate resilience, and socio-economic benefits. Unlike conventional ornamental gardens, where aesthetics are often the primary objective, carbon gardens are designed to function as net carbon sinks by maximizing atmospheric CO₂ capture through photosynthesis and promoting its long-term stabilization in aboveground biomass, root systems, and soil organic carbon. Their design emphasizes ecological functionality by increasing biomass production, maintaining continuous vegetative cover, minimizing soil disturbance, recycling organic residues, and improving soil biological activity, thereby reducing greenhouse gas emissions while enhancing ecosystem resilience (Lal, 2020; IPCC, 2023; Jarosz & Faber, 2025) [19, 17, 15]. Carbon gardens integrate multiple complementary components that collectively enhance carbon sequestration and environmental sustainability. These typically include:

- Trees, shrubs, and perennial plant species with high biomass production;
- Ground covers and cover crops for continuous soil

protection;

- Composting systems for recycling organic residues;
- Biochar and other stable organic amendments to increase long-term soil carbon storage;
- Rainwater harvesting and water-efficient irrigation systems;
- Soil conservation practices such as mulching, erosion control, and minimum soil disturbance; and
- Native, pollinator-friendly, and climate-resilient plant species that improve biodiversity and ecosystem stability (FAO, 2022; Singh *et al.*, 2024) [29, 8].

The effectiveness of carbon gardens arises from the integration of these components into a multifunctional landscape where biological carbon capture, soil carbon stabilization, and ecological restoration operate synergistically. In addition to climate change mitigation, carbon gardens contribute to improved soil fertility, enhanced water infiltration and retention, biodiversity conservation, urban cooling, food production, recreational opportunities, and overall landscape resilience. Their flexibility allows implementation across a wide range of settings, including residential gardens, institutional campuses, urban parks, community gardens, peri-urban landscapes, and agricultural field margins, making them a scalable and locally adaptable nature-based solution for sustainable development (IPCC, 2022, 2023; UNEP, 2024) [32, 14].

Viewed in this context, carbon gardens represent a practical landscape-scale application of carbon farming principles, translating scientific knowledge on carbon sequestration into accessible, multifunctional green spaces that simultaneously support climate mitigation, ecosystem restoration, and human well-being. As interest in carbon-negative land-use systems continues to grow, carbon gardens offer a promising framework for integrating environmental sustainability with productive and aesthetically appealing landscapes.

3. Scientific Basis of Carbon Gardens

The scientific foundation of carbon gardens lies in enhancing the terrestrial carbon cycle by increasing carbon capture through photosynthesis and promoting its long-term storage in plant biomass and soils. Carbon sequestration results from the interaction of plant physiological processes, soil microbial activity, organic matter dynamics, and sustainable land management practices. By integrating perennial vegetation, soil-conserving practices, and organic carbon inputs, carbon gardens enhance both carbon assimilation and the stability of stored carbon, thereby contributing to climate change mitigation and improved ecosystem functioning (Lal, 2020; IPCC, 2022, 2023; Khan *et al.*, 2026) [19, 18, 14]. A conceptual layout illustrating the major structural components of a carbon garden is presented in Figure 1.



Fig 1: Schematic representation of a carbon garden integrating trees, perennial vegetation, soil-building practices, composting, biochar, and water-harvesting components for enhanced carbon sequestration and ecosystem sustainability

3.1 Photosynthetic Carbon Capture

Photosynthesis is the primary mechanism through which carbon gardens remove atmospheric carbon dioxide (CO₂), converting it into carbohydrates that are allocated to leaves, stems, roots, flowers, fruits, and woody tissues, where a substantial proportion remains stored as plant biomass, particularly in perennial trees and shrubs that accumulate carbon over many years (IPCC, 2022; Khan *et al.*, 2026) [18, 14]. The efficiency of carbon capture is influenced by species composition, canopy architecture, leaf area index, photosynthetic capacity, growing season length, nutrient availability, and water supply. Consequently, carbon gardens emphasize diverse, perennial, high-biomass plant species and mixed-species plantings that sustain photosynthesis over extended periods, enhancing cumulative carbon sequestration, ecosystem resilience, and overall carbon storage compared with monoculture systems (FAO, 2022; Singh *et al.*, 2024) [29, 8].

3.2 Soil Carbon Sequestration

While vegetation captures atmospheric carbon, soils serve as the largest long-term carbon reservoir in carbon gardens. A substantial proportion of photosynthetically fixed carbon is transferred belowground through root growth, root exudation, root turnover, litter deposition, and microbial activity, where it is transformed into soil organic matter (SOM) and stabilized as soil organic carbon (SOC) through interactions with soil minerals and aggregates (Lal, 2020; IPCC, 2022; Khan *et al.*, 2026) [19, 18, 14].

The principal pathways contributing to soil carbon sequestration include:

- Root exudation supplying labile carbon to soil microorganisms;
- Root turnover and fine-root decomposition;
- Decomposition of leaf litter and pruning residues;
- Formation of microbial biomass and necromass; and
- Stabilization of organic matter within soil aggregates and mineral-associated organic carbon.

Carbon gardens enhance these pathways through compost

application, mulching, biochar incorporation, perennial ground cover, reduced soil disturbance, and continuous organic matter recycling, thereby improving soil structure, microbial diversity, nutrient cycling, and the quantity and long-term stability of SOC (Lehmann & Joseph, 2015; Li *et al.*, 2024; Khan *et al.*, 2026) [20, 21, 18].

3.3 Long-Term Carbon Storage

The climate mitigation potential of carbon gardens depends not only on the rate of carbon capture but also on the permanence of stored carbon. Perennial vegetation, particularly trees, shrubs, and other woody species, stores carbon in lignified tissues for decades or centuries, while stable soil organic carbon, especially mineral-associated organic matter and biochar-derived carbon, provides long-term belowground storage due to its slow decomposition (IPCC, 2022; FAO, 2022) [14, 8]. Carbon permanence is further enhanced by maintaining permanent vegetation cover, minimizing soil disturbance, preventing erosion, and continuously replenishing organic matter, thereby protecting above- and belowground carbon pools (Lehmann & Joseph, 2015; Lal, 2020; Khan *et al.*, 2026) [20, 19, 18]. Together, efficient photosynthetic carbon capture, enhanced soil carbon sequestration, and long-term carbon stabilization enable carbon gardens to function as resilient, multifunctional carbon sinks that remove atmospheric CO₂ while improving soil fertility, ecosystem productivity, biodiversity, and climate resilience, supporting the broader goals of carbon-negative farming and sustainable landscape management (IPCC, 2023; Singh *et al.*, 2024; Khan *et al.*, 2026) [29, 18, 15].

4. Core Principles of Carbon Garden Design

The effectiveness of carbon gardens depends on ecological design principles that maximize carbon capture, enhance carbon storage, and maintain long-term ecosystem resilience. These principles are derived from the scientific foundations of nature-based solutions, regenerative agriculture, carbon farming, agroforestry, and ecological restoration, where vegetation, soils, and biological processes interact to optimize carbon sequestration while delivering multiple ecosystem services. Collectively, these principles enable carbon gardens to function

as stable, productive, and climate-resilient landscapes (IPCC, 2022, 2023; Singh *et al.*, 2024; Khan *et al.*, 2026) ^[29, 18, 14].

4.1 Maximizing Photosynthetic Surface Area

The capacity of a carbon garden to capture atmospheric CO₂ is directly related to its total photosynthetically active surface area. Increasing vegetation density through multilayered planting systems comprising trees, shrubs, climbers, herbaceous perennials, and ground covers enhances canopy interception of solar radiation and extends the duration and intensity of photosynthesis. Such vertically stratified vegetation not only increases biomass production but also improves light-use efficiency, microclimatic regulation, and overall ecosystem productivity. Consequently, maximizing leaf area index (LAI) and maintaining year-round green cover are fundamental design objectives for increasing carbon fixation (FAO, 2022; IPCC, 2022; Khan *et al.*, 2026) ^[18, 14, 8].

4.2 Promoting Perennial Vegetation

Perennial vegetation forms the structural foundation of carbon gardens because it provides continuous carbon sequestration with minimal soil disturbance. Unlike annual crops, perennial trees, shrubs, grasses, and herbaceous species maintain extensive root systems that accumulate biomass over many years, increase soil organic carbon inputs, and reduce greenhouse gas emissions associated with repeated cultivation. Deep-rooted perennial species also improve nutrient cycling, water infiltration, drought tolerance, and long-term ecosystem stability. Therefore, incorporating long-lived native and climate-resilient perennial species substantially enhances both aboveground and belowground carbon storage (Lal, 2020; IPCC, 2022; Khan *et al.*, 2026) ^[19, 18, 14].

4.3 Enhancing Soil Organic Matter

Soil organic matter (SOM) is the principal reservoir of terrestrial carbon and plays a central role in sustaining soil health and ecosystem productivity. Carbon gardens enhance SOM through the continuous addition of compost, mulch, leaf litter, pruning residues, cover crop biomass, and other organic amendments that increase soil organic carbon (SOC) while stimulating microbial activity. The incorporation of biochar further improves carbon permanence by stabilizing organic carbon and enhancing nutrient retention and soil aggregation. Maintaining high SOM levels also improves soil fertility, water-holding capacity, cation exchange capacity, and biological diversity, thereby creating positive feedbacks that support continued carbon sequestration (Lehmann & Joseph, 2015; Lal, 2020; Li *et al.*, 2024; Khan *et al.*, 2026) ^[20, 19, 21, 18].

4.4 Minimizing Soil Disturbance

Soil disturbance accelerates the oxidation of organic matter, disrupts soil aggregates, increases CO₂ emissions, and reduces the stability of soil carbon pools. Accordingly, carbon gardens emphasize minimum soil disturbance through reduced or no-tillage practices, permanent soil cover, mulching, and careful management of planting operations. These practices preserve soil structure, protect microbial habitats, reduce erosion, and enhance the formation of stable soil organic carbon. Maintaining continuous vegetation cover further moderates soil temperature and moisture, creating favorable conditions for microbial carbon stabilization and long-term carbon storage (IPCC, 2022; Singh *et al.*, 2024; Khan *et al.*, 2026) ^[29, 18, 14].

4.5 Encouraging Biodiversity

Biological diversity is a defining feature of effective carbon

gardens because diverse ecosystems generally exhibit greater productivity, stability, and resilience than species-poor systems. Integrating trees, shrubs, perennial herbs, grasses, flowering plants, and native species enhances complementary resource use, extends the growing season, increases biomass production, and supports pollinators, beneficial insects, soil microorganisms, birds, and other wildlife. These interactions strengthen ecosystem functioning, nutrient cycling, resilience to pests, diseases, and climate extremes, while directly enhancing long-term carbon sequestration (FAO, 2022; Buma *et al.*, 2024; Khan *et al.*, 2026) ^[5, 18, 8].

Collectively, these five design principles provide the ecological foundation for carbon gardens, maximizing atmospheric carbon removal while enhancing soil health, biodiversity, water conservation, climate resilience, and sustainable landscape management (IPCC, 2023; Singh *et al.*, 2024; Khan *et al.*, 2026) ^[29, 18, 15].

4.6 Optimizing Resource-Use Efficiency

Optimizing resource-use efficiency is a key principle of carbon garden design, maximizing carbon sequestration while minimizing greenhouse gas emissions. Carbon gardens adopt circular resource-use strategies, including rainwater harvesting, drip irrigation, composting of garden residues, nutrient recycling, renewable energy-powered irrigation, and locally available organic amendments, to improve water- and nutrient-use efficiency, enhance soil biological activity, reduce dependence on synthetic fertilizers and fossil fuels, and lower the overall carbon footprint. Collectively, these climate-smart, low-input practices improve ecosystem resilience, economic sustainability, and long-term carbon sequestration (FAO, 2022; IPCC, 2022; Singh *et al.*, 2024; UNEP, 2024; Khan *et al.*, 2026) ^[29, 18, 32, 14, 8].

5. Components of a Carbon Garden

A carbon garden comprises diverse biological and structural components that function synergistically to maximize carbon sequestration, strengthen ecosystem resilience, and enhance ecosystem services through improved nutrient cycling, soil health, and water conservation (IPCC, 2022; Singh *et al.*, 2024; Khan *et al.*, 2026) ^[29, 18, 14]. The principal pathways of carbon capture and long-term storage within a carbon garden are illustrated in Figure 2.

5.1 Trees and Woody Perennials

Trees and woody perennials constitute the primary carbon reservoirs in carbon gardens owing to their high biomass production, deep root systems, and long life span. They sequester atmospheric CO₂ in woody tissues, roots, and litter while continuously contributing organic matter to the soil. Besides storing carbon for decades or centuries, trees improve microclimatic conditions, reduce erosion, enhance biodiversity, and support nutrient cycling, making them the backbone of carbon garden design (FAO, 2022; IPCC, 2022; Khan *et al.*, 2026) ^[18, 14, 8].

5.2 Shrubs and Understory Vegetation

Shrubs and understory vegetation increase vertical vegetation stratification, thereby improving light interception and overall ecosystem productivity. They contribute additional biomass, enhance belowground carbon inputs through extensive root systems, protect the soil surface, and provide habitat for pollinators and beneficial organisms. Their inclusion improves biodiversity, ecological stability, and the overall carbon

sequestration capacity of the garden (Buma *et al.*, 2024; Singh *et al.*, 2024) [5, 29].

5.3 Ground Covers

Ground-cover plants maintain continuous soil cover, reducing erosion, suppressing weeds, moderating soil temperature, and conserving soil moisture. Their dense root systems continuously supply organic carbon to the soil through root turnover and litter deposition while supporting soil microbial activity. Permanent ground cover also minimizes soil carbon losses by protecting the soil from physical disturbance and enhancing soil aggregate stability (Lal, 2020; IPCC, 2022; Khan *et al.*, 2026) [19, 18, 14].

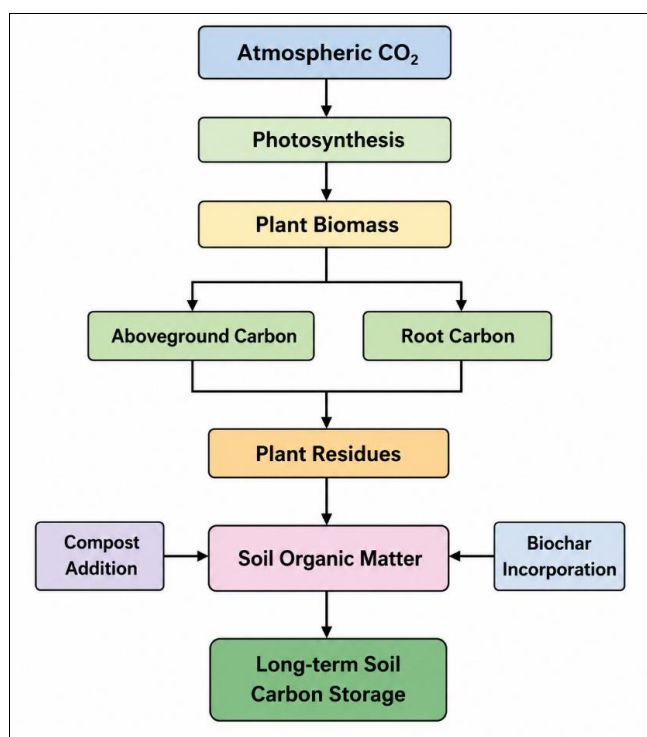


Fig 2: Major carbon capture and storage pathways in a carbon garden, illustrating the movement of atmospheric carbon into plant biomass and stable soil carbon pools

5.4 Compost Systems

Composting systems recycle plant residues and other biodegradable organic wastes into nutrient-rich compost that increases soil organic matter and soil organic carbon. Regular compost application improves soil fertility, microbial diversity, nutrient cycling, water-holding capacity, and aggregate stability while reducing methane emissions associated with uncontrolled decomposition of organic wastes. Compost therefore plays a central role in sustaining long-term carbon accumulation and soil health in carbon gardens (FAO, 2022; Khan *et al.*, 2026) [18, 8].

5.5 Biochar

Biochar is a stable carbon-rich material produced through the pyrolysis of biomass under limited oxygen conditions. Because of its high resistance to microbial decomposition, biochar can persist in soils for centuries, making it one of the most durable forms of terrestrial carbon storage. In addition to increasing soil carbon stocks, biochar improves soil structure, nutrient retention, cation exchange capacity, water-holding capacity, and microbial activity, thereby enhancing both carbon sequestration and plant productivity (Lehmann & Joseph, 2015; Singh *et al.*, 2024; Khan *et al.*, 2026) [20, 29, 18].

5.6 Water-Harvesting Structures

Water-harvesting structures such as rain gardens, swales, infiltration basins, contour trenches, and small retention ponds improve soil moisture, supporting plant growth, photosynthesis, biomass production, and belowground carbon inputs while reducing runoff and soil erosion. By enhancing water-use efficiency and sustaining vegetation growth, these structures indirectly increase long-term carbon sequestration and ecosystem resilience under changing climatic conditions (IPCC, 2022; FAO, 2022; Khan *et al.*, 2026) [18, 14, 8].

5.7 Soil Microbiome and Mycorrhizal Networks

The soil microbiome, including bacteria, fungi, and particularly arbuscular mycorrhizal fungi (AMF), is central to carbon cycling and long-term soil carbon stabilization. Root-associated microorganisms transform plant-derived carbon into microbial biomass and necromass, a portion of which is stabilized as persistent soil organic carbon. Mycorrhizal associations further enhance nutrient and water uptake, belowground carbon allocation, soil aggregation, and long-term carbon sequestration, making a diverse soil microbiome essential for maximizing carbon storage and ecosystem functioning in carbon gardens (Li *et al.*, 2024; Buma *et al.*, 2024; Khan *et al.*, 2026) [21, 5, 18].

5.8 Pollinator and biodiversity habitats

Habitats such as flowering plants, native vegetation, hedgerows, insect refuges, and small wetlands support pollinators and other beneficial organisms, enhancing pollination, natural pest regulation, nutrient cycling, ecosystem resilience, vegetation productivity, and biomass accumulation. Greater biodiversity also improves ecosystem stability and adaptive capacity under changing climatic conditions, indirectly promoting long-term carbon sequestration and sustained ecosystem services (FAO, 2022; IPCC, 2023; Buma *et al.*, 2024; Khan *et al.*, 2026) [5, 18, 15, 8].

Collectively, these components function as an integrated system in which vegetation, soils, organic amendments, water management, and biodiversity interact to maximize carbon capture, long-term storage, ecosystem resilience, and sustainable carbon-negative landscape management (IPCC, 2023; Singh *et al.*, 2024; Khan *et al.*, 2026) [29, 18, 15].

6. Carbon Sequestration Potential

The carbon sequestration potential of carbon gardens depends on the combined capacity of vegetation and soils to capture, store, and retain atmospheric carbon. Carbon accumulation varies with climate, plant species composition, vegetation age, soil type, management intensity, and carbon-enhancing practices such as compost application, biochar incorporation, perennial planting, and reduced soil disturbance. Despite variation among ecosystems, well-managed perennial landscapes consistently sequester more carbon than intensively managed annual systems because they combine continuous biomass production with greater long-term stabilization of soil organic carbon (SOC) (Lal, 2020; IPCC, 2022; Khan *et al.*, 2026) [19, 18, 14].

Carbon is stored in several interconnected pools. Aboveground biomass (trees, shrubs, and perennial herbs) serves as the primary living carbon reservoir, while belowground biomass (roots and rhizomes) contributes to SOC through root turnover and exudation and improves soil aggregation. However, SOC is the largest and most persistent carbon pool, formed through the continuous incorporation and stabilization of plant- and microbially derived organic matter. Biochar further enhances long-term carbon storage because of its resistance to decomposition, whereas compost increases soil organic matter,

stimulates microbial activity, and promotes the gradual accumulation of stable SOC (Lehmann & Joseph, 2015; Singh et al., 2024; Khan et al., 2026)^[20, 29, 18]. The major carbon storage

compartments within a carbon garden and their relative contributions to long-term carbon sequestration are summarized in Table 1.

Table 1: Major carbon storage compartments in carbon gardens and their primary mechanisms contributing to long-term carbon sequestration

Carbon Pool	Relative Contribution	Primary Carbon Storage Mechanism
Aboveground biomass	High	Carbon stored in stems, branches, leaves, and woody tissues of trees and shrubs
Root biomass	Moderate to High	Root growth, turnover, and rhizodeposition contributing carbon belowground
Soil organic carbon	Very High	Stabilized organic matter derived from plant residues, roots, and microbial biomass
Biochar carbon	High (Long-term)	Highly stable pyrogenic carbon resistant to decomposition
Compost-derived carbon	Moderate	Organic matter inputs that enhance soil carbon accumulation and microbial activity

The integration of these complementary carbon pools enables carbon gardens to function as durable net carbon sinks while enhancing soil fertility, water-holding capacity, biodiversity, and ecosystem resilience. Maximizing carbon sequestration therefore requires a systems-based approach that combines high-biomass perennial vegetation with practices that protect and stabilize soil carbon, supporting climate change mitigation and carbon-negative landscape management (IPCC, 2023; Buma et al., 2024; Khan et al., 2026)^[5, 18, 15]. Carbon sequestration potential is influenced by climate, soil properties, vegetation age and diversity, and management practices. Favorable climatic conditions, carbon-stabilizing soils, diverse perennial vegetation, and practices such as organic matter recycling, biochar application, reduced soil disturbance, and efficient water management enhance both carbon storage and its long-term stability, highlighting the importance of site-specific design and sustainable management (IPCC, 2022, 2023; Buma et al., 2024; Singh et al., 2024; Khan et al., 2026)^[5, 29, 18, 14].

7. Environmental Benefits

Beyond long-term carbon storage, carbon gardens provide multiple environmental co-benefits by integrating diverse perennial vegetation, healthy soils, and ecological management practices. They simultaneously support greenhouse gas mitigation, biodiversity conservation, soil restoration, hydrological regulation, microclimate improvement, ecosystem resilience, and climate adaptation, thereby enhancing the sustainability of urban and rural landscapes while contributing to several Sustainable Development Goals (SDGs) (Griscom et al., 2017; IPCC, 2023)^[11, 15]. Beyond carbon sequestration, the major ecosystem services provided by carbon gardens are summarized in Figure 3.

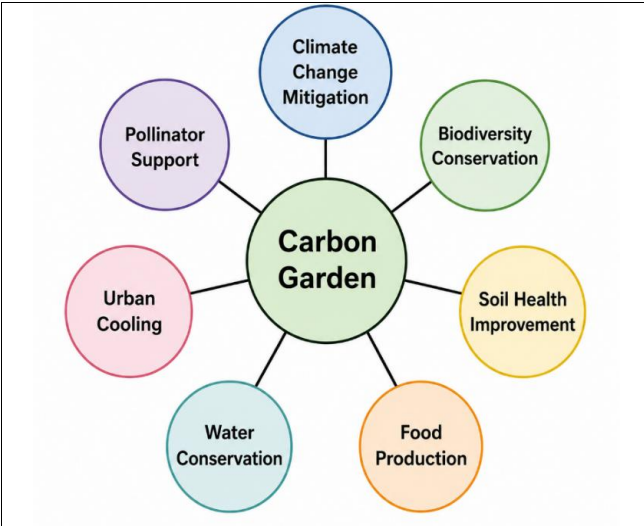


Fig 3: Multifunctional ecosystem services delivered by carbon gardens beyond carbon sequestration

7.1 Climate Change Mitigation

The primary environmental benefit of carbon gardens is the removal of atmospheric CO₂ through photosynthesis and its storage in aboveground biomass, roots, and soil organic matter. Trees, shrubs, perennial grasses, cover crops, and soil microorganisms function as long-term carbon sinks, while practices such as reduced soil disturbance, improved nutrient-use efficiency, lower dependence on synthetic fertilizers, and reduced fossil-fuel-intensive maintenance further decrease greenhouse gas emissions. Increased soil organic carbon also enhances resilience to drought and extreme weather, supporting climate adaptation (Lal, 2020; PCC, 2023; Khan et al., 2026)^[19, 18]. Nature-based climate solutions, including agroforestry and ecological restoration, could provide about one-third of the cost-effective climate mitigation needed by 2030 to achieve the Paris Agreement goals (Griscom et al., 2017)^[11].

7.2 Biodiversity Conservation

Carbon gardens promote biodiversity by integrating trees, shrubs, herbaceous plants, flowering species, and ground covers that support pollinators, birds, mammals, beneficial insects, soil fauna, and diverse microbial communities. Greater biodiversity enhances nutrient cycling, pollination, biological pest control, ecosystem stability, and resilience to environmental disturbances, while native and regionally adapted species strengthen ecosystem functioning and reduce invasive species risks (Isbell et al., 2017; FAO, 2021)^[16, 7]. Diverse plant communities also enhance carbon sequestration through greater productivity and ecosystem stability than monocultures.

7.3 Soil Health Improvement

Healthy soils are fundamental to carbon gardens. Organic inputs from leaf litter, root turnover, compost, mulch, and cover crops increase soil organic carbon, improving soil structure, aggregation, biological activity, porosity, aeration, root growth, and erosion resistance. Carbon-rich soils also enhance microbial-mediated nutrient cycling, long-term carbon stabilization, cation exchange capacity, nutrient availability, water-holding capacity, and pH buffering, thereby improving plant productivity while reducing fertilizer requirements (Ganie et al., 2016; Narayan et al., 2018; Lal, 2020; FAO, 2022)^[9, 25, 19, 8]. Consequently, carbon gardens support soil restoration, sustainable nutrient cycling, and long-term productivity.

7.4 Urban Heat Island Reduction

Carbon gardens mitigate the urban heat island effect through canopy shading, evapotranspiration, and increased vegetation cover. Trees reduce surface and air temperatures by intercepting solar radiation and dissipating heat, improving thermal comfort, reducing cooling energy demand and heat-related health risks, and enhancing urban livability. Integrating trees, green roofs, rain gardens, and vegetated corridors further strengthens

microclimate regulation while contributing to carbon sequestration and biodiversity conservation (Bowler *et al.*, 2010; IPCC, 2022) [4, 14].

7.5 Water Conservation

Carbon gardens improve water conservation through enhanced soil structure, increased organic matter, and diverse vegetation. Carbon-rich soils increase infiltration, water-holding capacity, groundwater recharge, and drought resilience while reducing runoff, erosion, evaporation, and sediment transport. Mulching, permanent vegetation, and deep-rooted perennial species further improve soil moisture retention, whereas vegetated landscapes filter nutrients and pollutants, enhancing water quality and aquatic ecosystem health (Blanco-Canqui & Lal, 2008; FAO, 2022) [2, 8]. These hydrological benefits are increasingly important under climate change.

8. Carbon Gardens and Food Security

Carbon gardens can simultaneously function as productive landscapes and long-term carbon sinks by integrating diverse edible plant species with perennial vegetation and soil-building practices. Such multifunctional systems enhance household food availability, improve dietary diversity, strengthen local food systems, and increase resilience to climate change while continuing to sequester atmospheric carbon in biomass and soils (FAO, 2021; IPCC, 2023) [15, 7]. Incorporating a variety of food-producing plants also promotes biodiversity, efficient resource use, and year-round ecosystem functioning.

- **Fruit trees:** Fruit trees such as apple, mango, citrus, guava, pear, and plum serve as long-lived carbon reservoirs by storing substantial amounts of carbon in woody biomass while producing nutrient-rich fruits. Their extensive root systems contribute to soil organic carbon accumulation, improve soil structure, and reduce erosion, making fruit trees an integral component of carbon gardens and climate-resilient food production systems (Lal, 2020; Nair *et al.*, 2021) [19, 24].
- **Vegetables:** Seasonal and perennial vegetables provide regular harvests while increasing ground cover and organic matter inputs through crop residues and root biomass. When grown using conservation practices such as mulching, compost application, crop rotation, and reduced tillage, vegetable production enhances soil carbon sequestration, nutrient cycling, and water-use efficiency without compromising productivity (Lal, 2020; FAO, 2022; Narayan *et al.*, 2018) [19, 25, 8].
- **Herbs:** Culinary herbs including basil, mint, coriander, rosemary, thyme, and oregano require relatively small growing spaces and can be integrated beneath trees or along garden borders. These species contribute to plant diversity, support pollinators and beneficial insects, provide continuous biomass inputs to the soil, and offer fresh culinary products with minimal environmental footprint (FAO, 2021) [7].
- **Medicinal plants:** Medicinal species such as aloe vera, ashwagandha, tulsi, lemongrass, and chamomile diversify carbon gardens while supporting traditional healthcare and livelihood opportunities. Their cultivation increases vegetation cover, enhances habitat diversity, and contributes organic residues that improve soil carbon storage and microbial activity (WHO, 2013; FAO, 2021) [7, 36].
- **Edible perennials:** Perennial vegetables and edible species, including asparagus, rhubarb, moringa, artichoke, and various perennial leafy greens, maintain continuous living

roots that enhance belowground carbon inputs, reduce soil disturbance, improve nutrient retention, and provide reliable food production over multiple years. Their permanent vegetation cover also increases ecosystem stability and long-term carbon sequestration compared with annual cropping systems (Toensmeier, 2016; IPCC, 2023) [31, 15].

- Overall, integrating fruit trees, vegetables, herbs, medicinal plants, and edible perennials transforms carbon gardens into multifunctional landscapes that simultaneously strengthen food security, improve nutritional diversity, enhance ecosystem resilience, and contribute to climate change mitigation through sustained carbon sequestration (Wani *et al.*, 2021; Wani *et al.*, 2023) [33, 34].

9. Carbon Gardens in Urban Environments

Urban areas offer significant potential for carbon sequestration through the strategic integration of vegetation into built environments. Although individual urban green spaces are relatively small, their cumulative contribution can substantially increase biomass and soil carbon storage while delivering multiple ecosystem services, including improved air quality, urban cooling, stormwater management, biodiversity conservation, and enhanced human well-being. Well-designed urban carbon gardens also foster environmental awareness and strengthen community participation in climate action and sustainable city development (IPCC, 2022; FAO, 2022) [14, 8].

- **Rooftop gardens:** Green roofs and rooftop gardens convert underutilized building surfaces into productive green spaces that sequester carbon in plant biomass and growing media while reducing building energy consumption through thermal insulation. They also mitigate the urban heat island effect, improve stormwater retention, filter airborne pollutants, and provide habitat for pollinators and other beneficial organisms, thereby enhancing urban environmental sustainability (Getter & Rowe, 2006; Oberndorfer *et al.*, 2007) [10, 27].
- **Community gardens:** Community gardens combine food production with environmental stewardship by cultivating vegetables, fruits, herbs, and ornamental plants in shared spaces. These gardens increase urban vegetation cover, enhance soil organic carbon through composting and organic management, promote biodiversity, and strengthen social cohesion, food security, and public engagement in climate-resilient urban development (Lin *et al.*, 2015; FAO, 2022) [22, 8].
- **School gardens:** School gardens function as living laboratories where students learn about sustainable agriculture, biodiversity, climate change, and environmental conservation through hands-on experiences. The incorporation of trees, shrubs, vegetables, and flowering plants increases local carbon sequestration while fostering environmental literacy, healthy eating habits, and long-term stewardship of natural resources (Blair, 2009; FAO, 2021;) [1, 7].
- **Institutional landscapes:** Green spaces within universities, hospitals, government offices, and commercial campuses can be designed as carbon gardens by incorporating native trees, perennial vegetation, rain gardens, and pollinator-friendly plantings. Such landscapes increase carbon storage, reduce cooling demands, improve air quality, enhance biodiversity, and demonstrate sustainable land management practices to the wider community (Livesley *et al.*, 2016; IPCC, 2022) [23, 14].
- **Residential backyards:** Home gardens and residential

backyards collectively represent a substantial yet often underutilized resource for urban carbon sequestration. Integrating fruit trees, shrubs, vegetables, composting systems, and perennial ground covers enhances aboveground and belowground carbon storage while supplying fresh food, improving soil fertility, conserving water, and creating habitat for pollinators and beneficial wildlife (Cameron *et al.*, 2012; FAO, 2022) [6, 8].

Collectively, rooftop gardens, community gardens, school gardens, institutional landscapes, and residential backyards transform urban environments into multifunctional carbon sinks that simultaneously mitigate climate change, improve ecosystem services, strengthen food security, and enhance the quality of urban life.

10. Integration with Carbon-Negative Farming

Carbon gardens exemplify the principles of carbon-negative farming by combining practices that actively remove atmospheric carbon dioxide while minimizing greenhouse gas emissions and enhancing ecosystem resilience. Through the integration of perennial vegetation, regenerative soil management, and circular biomass utilization, these systems function as small-scale models of carbon-negative land use that can be adapted to larger agricultural landscapes (Lal, 2020; IPCC, 2023; Khan *et al.*, 2026) [19, 18, 15]. The contribution of carbon gardens to carbon-negative farming and climate-resilient landscapes is conceptually illustrated in Figure 4.

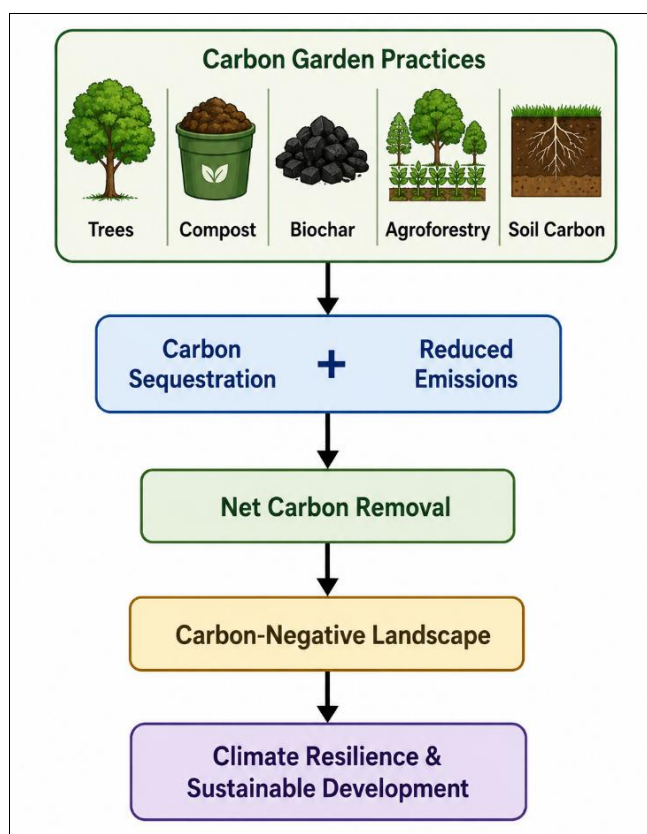


Fig 4: Role of carbon gardens in achieving carbon-negative land management through enhanced carbon sequestration and reduced greenhouse gas emissions.

- **Continuous carbon capture:** The incorporation of trees, shrubs, perennial grasses, and ground covers ensures year-round photosynthetic carbon uptake and long-term storage

of carbon in aboveground biomass, roots, and soil organic matter. Continuous vegetative cover also minimizes carbon losses associated with bare soil and erosion (Bossio *et al.*, 2020; IPCC, 2023) [3, 15].

- **Soil carbon enhancement:** Practices such as reduced soil disturbance, mulching, compost application, cover cropping, and permanent vegetation increase soil organic carbon stocks by enhancing organic matter inputs and reducing decomposition rates. Improved soil carbon also strengthens nutrient cycling, water retention, and soil biological activity, thereby increasing ecosystem resilience (Lal, 2020; Wani *et al.*, 2021; FAO, 2022) [19, 33, 8].
- **Biochar utilization:** Incorporating biochar into carbon gardens provides a stable form of carbon that can remain in soils for centuries while improving soil fertility, cation exchange capacity, moisture retention, and microbial activity. Biochar simultaneously sequesters carbon and enhances crop productivity, making it a key component of carbon-negative farming systems (Lehmann & Joseph, 2015; Woolf *et al.*, 2021) [20, 35].
- **Organic residue recycling:** Recycling leaf litter, pruning residues, crop wastes, and kitchen compost within the garden reduces waste disposal emissions while returning nutrients and organic carbon to the soil. This circular nutrient management decreases reliance on synthetic fertilizers and promotes long-term soil carbon accumulation (Smith *et al.*, 2020; FAO, 2022; Wani *et al.*, 2023) [30, 34, 8].
- **Agroforestry integration:** Combining trees with food crops, herbs, or forage species increases total biomass production and carbon storage while improving nutrient recycling, microclimate regulation, biodiversity, and farm resilience. Agroforestry systems consistently outperform monocultures in long-term carbon sequestration because they store carbon in both woody biomass and soils (Nair *et al.*, 2021; IPCC, 2023) [24, 15].
- **Biodiversity conservation:** Diverse plant communities support pollinators, beneficial insects, birds, soil microorganisms, and other wildlife that sustain ecosystem functions. Higher biodiversity enhances ecosystem productivity, stability, and resistance to climatic and biological disturbances, thereby supporting long-term carbon sequestration and sustainable food production (Isbell *et al.*, 2017; IPBES, 2019) [16, 12].

By integrating these complementary practices, carbon gardens serve as practical demonstration models for carbon-negative farming, illustrating how multifunctional landscapes can simultaneously sequester carbon, restore ecosystem functions, improve food production, and enhance climate resilience. Their successful implementation at household, institutional, and community scales provides valuable insights for scaling carbon-negative approaches to farms and broader agricultural landscapes.

11. Challenges and limitations

Despite their considerable environmental and socio-economic benefits, the widespread adoption of carbon gardens faces several technical, economic, and institutional challenges. Overcoming these barriers through supportive policies, scientific monitoring, public engagement, and capacity building will be essential for maximizing the contribution of carbon gardens to climate change mitigation and sustainable landscape management (FAO, 2022; IPCC, 2023) [15, 8].

- **Limited public awareness:** The concept of carbon gardens

remains unfamiliar to many landowners, urban residents, and local authorities. Limited understanding of carbon sequestration processes and the long-term ecological and economic benefits of nature-based solutions often restricts adoption. Public education, demonstration sites, and community outreach programs are therefore essential to increase awareness and encourage participation in carbon-positive landscape management (FAO, 2022; IPCC, 2023) [15, 8].

- **Difficulties in measuring carbon sequestration:** Accurate quantification of carbon stored in vegetation and soils remains one of the greatest challenges. Carbon sequestration varies with plant species, soil type, climate, management practices, and ecosystem age, making standardized assessment difficult. Reliable monitoring requires consistent sampling protocols, long-term measurements, and increasingly, remote sensing and digital carbon accounting tools to improve verification and reporting (Smith *et al.*, 2020; IPCC, 2023) [30, 15].
- **Initial establishment costs:** Establishing carbon gardens often involves significant upfront investments for site preparation, planting materials, irrigation infrastructure, compost or biochar application, and landscape design. Although these systems generally provide long-term environmental and economic benefits through reduced maintenance inputs and ecosystem services, the initial costs can discourage adoption without financial incentives, grants, or carbon-credit support (Bossio *et al.*, 2020; FAO, 2022) [3, 8].
- **Land availability constraints in urban areas:** Rapid urbanization, competing land uses, and high land values limit opportunities for developing new green spaces in cities. Consequently, integrating carbon gardens into rooftops, balconies, institutional campuses, roadside verges, vacant lots, and other underutilized urban spaces becomes critical for expanding urban carbon sequestration without competing with essential infrastructure (Livesley *et al.*, 2016; IPCC, 2022) [23, 14].
- **Long-term maintenance requirements:** The effectiveness of carbon gardens depends on sustained management, including irrigation during establishment, pruning, mulching, compost application, invasive species control, and replacement of dead plants. Neglect can reduce plant survival, biodiversity, and carbon sequestration potential. Community participation, institutional support, and long-term management plans are therefore necessary to maintain ecosystem health and ensure continued carbon storage (Cameron *et al.*, 2012; FAO, 2022) [6, 8].

Addressing these limitations requires integrated policy support, financial incentives, standardized carbon accounting methodologies, technical extension services, and public education programs. Advances in digital monitoring technologies, geographic information systems (GIS), remote sensing, and internationally harmonized carbon accounting frameworks will further improve the measurement, verification, and scaling of carbon gardens as effective nature-based climate solutions (Smith *et al.*, 2020; IPCC, 2023) [30, 15].

12. Conclusion and future perspectives

Carbon gardens represent a practical, scalable, and multifunctional nature-based solution for addressing climate change while enhancing ecosystem resilience. By integrating carbon sequestration with biodiversity conservation, soil

restoration, water conservation, and sustainable food production, they transform urban, peri-urban, and rural landscapes into productive long-term carbon sinks. Emerging advances in remote sensing, carbon accounting, biochar technologies, and climate-smart landscape design are expected to improve their effectiveness, monitoring, and wider adoption. Furthermore, the incorporation of carbon gardens into climate policies, urban planning, ecosystem restoration initiatives, and carbon credit mechanisms can provide additional incentives for their establishment and long-term management. As awareness, scientific understanding, and policy support continue to grow, carbon gardens have the potential to become an integral component of carbon-negative development pathways and resilient, sustainable landscapes for the future.

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