

Review Article

A comprehensive overview on Sustainable Vegetable gardening: Eco-friendly approaches to home grown production

Abstract

Sustainable vegetable gardening is an eco-friendly practice that integrates organic farming principles, resource conservation, and biodiversity promotion to produce nutritious, chemical-free food while minimizing environmental impact. This approach emphasizes soil health through the use of organic amendments, crop rotation, composting, and mulching to improve fertility and water retention. Water conservation techniques, such as drip irrigation and rainwater harvesting, are employed to optimize water use, especially in arid regions. Pest and disease management relies on integrated pest management (IPM), biological controls, companion planting, and the use of organic pesticides to reduce chemical input while maintaining crop health. Sustainable homegrown produce has been shown to have superior nutritional content compared to commercially grown produce, and the avoidance of synthetic chemicals reduces the risk of pesticide residue exposure. Gardening fosters healthy eating habits by connecting individuals to their food sources, encouraging the consumption of fresh, unprocessed vegetables, and contributing to food security. The mental and physical health benefits of gardening, including reduced stress, increased physical activity, and improved mental well-being, further highlight its holistic value. However, challenges such as the initial setup costs, time investment, pest management, and knowledge gaps can hinder widespread adoption. Addressing these challenges requires greater access to resources, educational initiatives, and the development of climate-resilient practices tailored to specific regions. Future trends in sustainable gardening include the adoption of technological innovations, such as smart irrigation systems, automation, and vertical farming, which offer scalable solutions for urban and small-scale gardeners. The COVID-19 pandemic has underscored the importance of resilient, local food systems, and sustainable gardening is poised to play a critical role in addressing future food security concerns.

Keywords: *Sustainable, Gardening, Organic, Biodiversity, Composting, Nutritional, IPM, Urban, Irrigation, Heirloom*

I. Introduction

Sustainable vegetable gardening involves cultivating vegetables using eco-friendly methods that ensure long-term resource availability without harming the environment. It minimizes the use of synthetic fertilizers and pesticides, instead relying on organic practices that promote soil fertility and biodiversity. The goal is to create a self-sustaining system that cycles nutrients efficiently and reduces waste, producing high-quality vegetables while preserving environmental health [1]. Home-grown produce offers fresh, nutritious food, improves food security, and reduces the carbon footprint associated with transporting produce. It is also free from the chemicals used in commercial farming, providing a healthier

option. Home gardening fosters self-reliance and encourages biodiversity by growing diverse crops and heirloom varieties. Gardening in urban areas has been shown to reduce stress and improve physical and mental health. It can also address food deserts, improving access to fresh, nutritious food [2, 3]. Eco-friendly gardening techniques focus on protecting the environment and conserving resources. Organic gardening, which avoids synthetic chemicals and uses natural fertilizers like compost, improves soil fertility and reduces irrigation needs. Composting recycles organic matter into the soil, enhancing its water retention and structure. Integrated pest management (IPM) uses biological controls like beneficial insects and companion planting to manage pests, reducing reliance on harmful pesticides and supporting local ecosystems. Water conservation methods such as drip irrigation, mulching, and rainwater harvesting are also essential, particularly in water-scarce areas. These practices help to minimize water use and protect valuable resources [4, 5]. Eco-friendly approaches encourage using native plant species that require fewer inputs and provide habitat for wildlife, supporting broader ecological health in the garden.

II. Principles of Sustainable Vegetable Gardening

The principles of sustainable vegetable gardening focus on conserving natural resources like water, soil, and energy. Efficient use of resources is key to maintaining long-term productivity. Techniques like drip irrigation reduce water usage by up to 50% and improve crop yields, while rainwater harvesting lessens reliance on municipal supplies. Soil conservation practices, such as mulching, crop rotation, and cover cropping, help maintain soil health, reduce erosion, and preserve nutrients. Mulching conserves moisture and prevents erosion, while crop rotation maintains soil fertility and reduces pests [6, 7]. Minimizing environmental impact is essential, and reducing pollution, greenhouse gas emissions, and ecological disruption plays a significant role. Synthetic fertilizers and pesticides are avoided in favor of organic alternatives like compost, which support soil and plant health without harming ecosystems. Integrated Pest Management (IPM) combines biological, cultural, and mechanical controls to manage pests, encouraging natural predators and minimizing chemical interventions. Sustainable gardening reduces the carbon footprint by producing food locally and reducing methane emissions through composting [8, 9, 10]. Biodiversity is central to sustainable gardening, supporting ecosystem resilience and promoting soil health. Companion planting and the use of heirloom seed varieties enhance biodiversity by attracting beneficial organisms like pollinators and pest predators. These practices reduce the need for chemical inputs and contribute to the garden's self-sustainability. Creating diverse habitats, such as wildflower borders and ponds, encourages wildlife that supports the garden's health [11, 12]. Organic gardening aligns with sustainability by focusing on natural processes. Organic practices, such as composting, green manures, and biological pest controls, build soil fertility and reduce waste. Composting transforms organic waste into nutrient-rich material, supporting soil health. Organic pest management uses natural methods, such as beneficial insects and crop rotation, to control pests without chemicals. Soil health is maintained through practices like cover cropping, which protects the soil and improves fertility [13, 14].

III. Soil Health and Management

Healthy soil is essential for sustainable vegetable gardening as it provides nutrients, water, and a habitat for beneficial microorganisms, promoting plant growth and biodiversity. It also acts as a carbon sink, mitigating climate change by sequestering atmospheric carbon. Soil health is critical for ecosystem services like nutrient cycling and water filtration, directly affecting plant vitality and yield. Poor soil management leads to nutrient depletion and erosion, making soil health crucial for long-term

sustainability [15]. Organic amendments, such as compost, manure, and green manures, improve soil fertility, water retention, and microbial activity without the negative environmental impacts of synthetic fertilizers. These organic inputs enhance soil structure and reduce the risk of water contamination, promoting the activity of beneficial organisms like earthworms and microbes [16, 17]. Mulching, which involves covering soil with organic or inorganic materials, helps conserve moisture, regulate soil temperature, suppress weeds, and prevent erosion. Organic mulches also improve soil structure as they decompose, adding organic matter. Mulching is particularly beneficial in arid regions, where water conservation is crucial [18]. Composting and vermicomposting recycle organic waste into nutrient-rich compost, which boosts soil fertility and reduces greenhouse gas emissions. Vermicomposting, using worms to accelerate decomposition, produces nutrient-dense worm castings that enrich soil health and microbial activity [19]. Crop rotation and cover cropping are essential for maintaining soil fertility. Crop rotation breaks pest cycles and reduces soil nutrient depletion by alternating crops with different nutrient needs, such as nitrogen-fixing legumes. Cover cropping, planting crops like clover or rye between rotations, prevents erosion and enriches the soil with organic matter, improving structure and fertility [20]. Both practices play a vital role in promoting sustainable gardening and maintaining productive, healthy soils.

IV. Water Conservation and Management

A. Efficient Irrigation Techniques

Water conservation is a critical aspect of sustainable vegetable gardening, particularly in regions facing water scarcity. Efficient irrigation techniques, such as drip irrigation and soaker hoses, ensure that water is delivered directly to the plant roots, minimizing evaporation and runoff. Drip irrigation systems can significantly reduce water usage compared to overhead sprinklers, which are less precise and lead to higher water losses due to evaporation and wind drift. Efficient irrigation techniques help to maintain consistent soil moisture levels, which is essential for plant health and productivity. Soil moisture sensors can be used in conjunction with these systems to monitor soil moisture levels and reduce unnecessary watering, further improving water use efficiency [21].

B. Rainwater Harvesting

Rainwater harvesting is a sustainable method of collecting and storing rainwater for use in the garden, reducing reliance on municipal water supplies. This practice not only conserves water but also reduces stormwater runoff, which can lead to soil erosion and water pollution. Rain barrels and cisterns can be used to collect rainwater from rooftops, which can then be used for irrigation during dry periods. By utilizing rainwater, gardeners can reduce their water footprint and contribute to sustainable water management practices. In addition, rainwater is often free of the salts and chemicals found in treated municipal water, making it beneficial for plants and soil [22].

C. Use of Drip Irrigation Systems

Drip irrigation is a highly efficient irrigation method that delivers water directly to the root zone of plants, reducing water waste and improving plant health. Studies have shown that drip irrigation can reduce water usage by up to 50% compared to traditional sprinkler systems, while also improving crop yields. The system works by releasing small amounts of water through emitters placed at the base of each plant,

ensuring that the soil remains consistently moist without becoming waterlogged. This precision watering method not only conserves water but also reduces the risk of diseases caused by excess moisture, such as root rot and fungal infections. Drip irrigation is particularly beneficial in arid and semi-arid regions where water conservation is critical [23].

D. Drought-resistant Vegetable Varieties

Drought-resistant vegetable varieties are an essential component of water conservation in sustainable gardening. These varieties have been bred or selected for their ability to thrive with minimal water, making them ideal for regions prone to drought or water scarcity. Drought-resistant vegetables, such as certain types of tomatoes, peppers, and beans, have adaptations that allow them to conserve water, such as deeper root systems or reduced leaf surface area. By growing drought-tolerant varieties, gardeners can reduce their water usage without sacrificing yields, contributing to more sustainable water management practices in vegetable gardening [24].

V. Organic Pest and Disease Management

A. Integrated Pest Management (IPM)

Integrated Pest Management (IPM) is a critical approach in sustainable gardening that seeks to manage pests and diseases by integrating various methods to minimize the reliance on chemical pesticides. IPM combines biological, cultural, physical, and chemical strategies to reduce pest populations to economically acceptable levels while minimizing risks to the environment, humans, and non-target organisms. The primary goal of IPM is not the eradication of pests but the management of pest populations in a way that preserves the ecological balance within the garden. Cultural controls, such as crop rotation and sanitation, prevent the buildup of pests, while biological controls introduce natural predators to keep pest populations in check. Physical barriers, such as row covers, can also be used to block pests from accessing plants [25]. When necessary, IPM may involve the targeted use of organic pesticides that are less harmful to the environment. This approach not only reduces the risk of pest resistance to chemicals but also preserves beneficial insects and other organisms that contribute to a healthy garden ecosystem.

B. Biological Pest Control Methods

Biological pest control involves the use of living organisms, such as predators, parasitoids, and pathogens, to control pest populations in a sustainable and environmentally friendly manner. This method harnesses natural relationships within ecosystems to keep pest numbers in check without the need for chemical interventions. For example, ladybugs (Coccinellidae) and lacewings (Chrysopidae) are commonly introduced to control aphid populations, while predatory mites (Phytoseiidae) can be used to manage spider mites. Parasitoid wasps (*Trichogramma* spp.), which lay their eggs inside pest larvae, can effectively control caterpillars and other insect pests [26]. In addition to predators and parasitoids, certain microbial agents, such as *Bacillus thuringiensis* (Bt), are used to infect and kill specific insect pests without harming beneficial insects or other wildlife. Biological control methods align with sustainable gardening principles by promoting biodiversity and reducing the need for chemical pesticides that can harm non-target organisms and disrupt ecological balance.

C. Companion Planting for Natural Pest Deterrence

Companion planting is a technique that involves growing certain plants together to enhance their growth and deter pests. This method is based on the idea that some plants have natural properties that repel pests or attract beneficial insects that feed on pests. For example, marigolds (*Tagetes* spp.) are often planted alongside vegetables to deter nematodes and other soil-dwelling pests, while basil (*Ocimum basilicum*) is known to repel aphids, whiteflies, and mosquitoes when planted near tomatoes [27]. Similarly, nasturtiums (*Tropaeolum* spp.) can be used as a trap crop to attract aphids away from other plants, reducing the need for chemical interventions. In addition to pest control, companion planting can improve soil health, enhance nutrient availability, and increase overall garden productivity by fostering beneficial plant interactions. This method is a key component of organic gardening, as it reduces the reliance on synthetic pesticides and promotes a more diverse and resilient garden ecosystem.

D. Use of Organic Pesticides and Fungicides

Organic pesticides and fungicides are essential tools in sustainable gardening, providing a means to control pests and diseases without the harmful environmental effects associated with synthetic chemicals. Organic pesticides are derived from natural sources, such as plants, minerals, or microbes, and are designed to target pests with minimal impact on non-target organisms and ecosystems [28]. Neem oil (*Azadirachta indica*), for instance, is a widely used organic pesticide that disrupts the life cycle of pests, including aphids, whiteflies, and caterpillars, while being safe for beneficial insects like bees and ladybugs. Pyrethrin, derived from chrysanthemum flowers, is another organic pesticide that is effective against a wide range of insect pests. Organic fungicides, such as copper-based compounds or sulfur, can be used to manage fungal diseases like powdery mildew and blight, while also being less harmful to the environment compared to synthetic fungicides. By using organic pest and disease management tools, gardeners can maintain healthy crops while minimizing their ecological footprint and promoting a more sustainable gardening practice.

VI. Climate-resilient Gardening Practices

A. Adaptation to Climate Change

Climate change poses significant challenges to gardening, as rising temperatures, changing precipitation patterns, and increased frequency of extreme weather events can affect plant growth, water availability, and pest populations [29]. Climate-resilient gardening practices involve adapting to these changes by choosing plant varieties that can withstand heat, drought, or excessive rainfall and by modifying gardening techniques to conserve resources and reduce vulnerability. One key strategy is improving soil health, as healthy soils with high organic matter content are better able to retain moisture, mitigate temperature fluctuations, and support resilient plant growth. Gardeners can adjust planting schedules to account for longer growing seasons or changing frost dates, allowing crops to mature before extreme weather events occur. Using shade structures, windbreaks, and mulch can also help protect plants from heat stress and reduce the impact of climate variability on garden productivity [30].

B. Use of Season Extension Techniques (e.g., Greenhouses, Cold Frames)

Season extension techniques allow gardeners to grow vegetables beyond the typical growing season, providing protection from frost, heat, or excessive rainfall. Greenhouses, cold frames, and hoop houses

are common tools used to create controlled environments where temperature, humidity, and light levels can be managed to optimize plant growth. These structures can extend the growing season by several weeks or even months, enabling gardeners to grow cold-sensitive crops in cooler climates or start plants earlier in the spring. Cold frames, which are simple, low-cost structures made of transparent materials, trap solar heat to create a warm environment for plants, protecting them from frost and cold temperatures. Greenhouses provide more extensive protection and allow for year-round cultivation of vegetables, flowers, and other crops. By utilizing season extension techniques, gardeners can adapt to climate variability and ensure a continuous supply of fresh produce throughout the year [31].

C. Growing Climate-appropriate Vegetable Varieties

Growing vegetable varieties that are well-suited to the local climate is essential for climate-resilient gardening. Climate-appropriate varieties are typically more resistant to temperature extremes, drought, or high humidity, and require fewer inputs in terms of water and pest control. In arid regions, drought-tolerant varieties such as tepary beans (*Phaseolus acutifolius*) or certain tomato cultivars have been bred to thrive with minimal water. In areas prone to excessive rainfall, flood-tolerant crops like swamp cabbage (*Ipomoea aquatica*) can be more successful than traditional crops. Choosing locally adapted heirloom varieties is also a valuable strategy, as these plants have evolved over time to thrive in specific climate conditions, making them more resilient to environmental stresses. By selecting vegetable varieties that are adapted to their climate, gardeners can reduce resource use and improve the sustainability of their gardening practices [32].

D. Reducing Carbon Footprint in Gardening

Gardening, when done sustainably, can contribute to reducing carbon emissions by sequestering carbon in the soil, reducing the need for food transportation, and minimizing the use of synthetic inputs. One of the primary ways to reduce the carbon footprint of gardening is through the use of organic and regenerative practices that enhance soil health and increase soil carbon storage. Healthy soils with high organic matter content can sequester significant amounts of carbon, mitigating the effects of climate change. In addition, home gardening eliminates the need for transporting produce over long distances, thereby reducing greenhouse gas emissions from transportation. Using renewable energy sources for powering garden tools or irrigation systems, such as solar-powered water pumps, further reduces the carbon footprint of gardening [33]. Finally, minimizing the use of synthetic fertilizers and pesticides, which are energy-intensive to produce and contribute to nitrous oxide emissions, helps lower the overall environmental impact of gardening. By adopting these practices, gardeners can contribute to climate mitigation efforts while growing food in an environmentally sustainable manner.

VII. Sustainable Garden Design and Layout

A. Raised Beds and Container Gardening

Raised beds and container gardening are vital elements in sustainable garden design, providing an efficient use of space, improving soil quality, and reducing resource use. Raised beds are elevated garden plots that allow for better control over soil composition, drainage, and plant spacing. They also help in reducing soil compaction, which is beneficial for root growth and soil health [34]. Raised beds are

particularly useful in areas where the native soil may be poor or contaminated, as they allow gardeners to create a controlled growing environment by introducing high-quality, nutrient-rich soil. Furthermore, raised beds help retain moisture and can reduce the need for excessive irrigation. Container gardening, which involves growing plants in pots or other containers, is another effective method for optimizing space, especially in urban environments where ground space may be limited. Containers can be moved to optimize sunlight exposure and are useful for growing vegetables in small spaces such as balconies or rooftops. Both raised beds and container gardening offer flexibility and ease of access, making them suitable for individuals with physical limitations. These gardening techniques contribute to sustainability by promoting water conservation, efficient use of space, and improved crop productivity [35].

B. Vertical Gardening Techniques

Vertical gardening is a space-saving technique that involves growing plants upwards using trellises, walls, or vertical planters. This method maximizes the use of available space and is ideal for small-scale or urban gardening where horizontal space is limited. Vertical gardening can increase the yield of crops such as beans, cucumbers, tomatoes, and other vining plants by allowing them to grow vertically instead of sprawling on the ground. Vertical gardening systems also improve air circulation around plants, reducing the incidence of fungal diseases and pests that thrive in humid, crowded conditions. In addition to its practical benefits, vertical gardening enhances the aesthetic appeal of garden spaces and can be integrated into architectural designs such as green walls and living facades. These systems can also contribute to building insulation and improve air quality in urban environments by absorbing pollutants and carbon dioxide [36]. Vertical gardening aligns with sustainable practices by promoting efficient use of space, reducing resource inputs, and contributing to environmental health in dense urban areas.

C. Use of Native Plants for Pollinators and Soil Enrichment

The use of native plants in garden design plays a critical role in promoting biodiversity, supporting pollinators, and enhancing soil health. Native plants are species that have evolved in a particular region and are adapted to the local climate, soil, and ecological conditions. These plants require fewer resources, such as water and fertilizers, and are more resistant to pests and diseases than non-native species, making them an integral part of sustainable gardening. Native plants also provide vital habitat and food sources for pollinators such as bees, butterflies, and birds, which are essential for the pollination of many crops. In addition to supporting biodiversity, native plants can improve soil health by promoting the growth of beneficial microbes and enhancing nutrient cycling. Some native plants, such as legumes, fix nitrogen in the soil, enriching it for future crops. Incorporating native plants into sustainable garden design not only benefits the ecosystem but also reduces the need for chemical inputs, making the garden more resilient and environmentally friendly [37].

D. Designing for Maximum Sunlight Exposure

Designing a garden to maximize sunlight exposure is crucial for optimizing plant growth and ensuring high yields, as sunlight is a primary energy source for photosynthesis. In sustainable garden design, it is essential to consider the orientation of the garden and the positioning of plants to capture the most sunlight throughout the day. South-facing gardens typically receive the most sunlight in the northern hemisphere, while north-facing gardens are optimal in the southern hemisphere. In addition to garden orientation, the placement of taller plants at the back of the garden and shorter plants at the front ensures

that all plants receive adequate sunlight without being shaded by others. Raised beds, vertical gardening, and container gardening can also be strategically positioned to make the best use of available sunlight, particularly in urban environments where buildings or other structures may block light. Maximizing sunlight exposure not only improves plant growth but also reduces the need for supplemental lighting or energy inputs, contributing to a more sustainable gardening practice [38].

VIII. Seed Saving and Heirloom Varieties

A. Importance of Heirloom and Non-GMO Seeds

Heirloom seeds are open-pollinated varieties that have been passed down through generations, often for their superior flavor, nutritional value, and adaptability to local growing conditions (Table-1). Unlike genetically modified organisms (GMOs), heirloom seeds are not engineered in laboratories, making them more genetically diverse and resilient to environmental stresses. The use of heirloom seeds in sustainable gardening promotes biodiversity and preserves plant genetic resources, which are critical for food security in the face of climate change. Heirloom varieties are often better adapted to organic growing conditions, requiring fewer chemical inputs and being more resistant to pests and diseases [39].

B. Techniques for Saving Seeds

Seed saving is a sustainable practice that allows gardeners to collect and store seeds from their crops for future planting. This practice reduces reliance on commercial seed suppliers and contributes to the preservation of plant genetic diversity. Techniques for saving seeds vary depending on the plant species but generally involve allowing the plant to mature fully, harvesting the seeds, cleaning them to remove debris, and storing them in a cool, dry place to maintain viability. For example, tomato seeds can be fermented to remove the gelatinous coating before drying and storing. Seed saving not only ensures a sustainable supply of seeds for future gardening seasons but also allows gardeners to select and propagate plants that are best suited to their local growing conditions.

C. Benefits of Seed Diversity

Maintaining seed diversity is essential for creating resilient agricultural systems that can adapt to changing environmental conditions, pests, and diseases. Genetic diversity in seeds allows plants to develop different traits, such as drought tolerance, disease resistance, or enhanced nutritional content, which are critical for sustainable gardening in the face of climate variability [40]. Seed diversity also contributes to a more vibrant and diverse food system, preserving unique plant varieties that might otherwise be lost in the commercial seed market dominated by a few large corporations. By promoting seed diversity, gardeners contribute to the long-term sustainability and resilience of agricultural ecosystems.

D. Seed Banks and Community Sharing Initiatives

Seed banks and community sharing initiatives are vital resources for preserving plant genetic diversity and promoting access to heirloom and non-GMO seeds. Seed banks, such as the Svalbard Global Seed Vault, store seeds from around the world to ensure that plant varieties are protected from extinction due to environmental disasters, war, or other threats. Community seed exchanges and sharing initiatives allow gardeners to access diverse seed varieties and share their own saved seeds, fostering local biodiversity and

strengthening community resilience [41]. These initiatives support sustainable gardening practices by promoting seed sovereignty and reducing dependence on commercial seed markets.

Table: 1 Seed Saving and Heirloom Varieties for Sustainable Vegetable Gardening: Eco-friendly Approaches to Home-grown Produce (Source: [40], [41])

Aspect	Seed Saving	Heirloom Varieties	Environmental Benefits	Community Impact
Definition	Collecting seeds from one season to use in the next, promoting self-reliance.	Traditional plant varieties passed down through generations, preserving genetic diversity and local adaptation.	Reduces industrial seed production and transportation, lowering the carbon footprint.	Encourages local exchange and preservation of heirloom seeds, fostering community connections.
Genetic Diversity	Helps maintain plant varieties that perform well in local conditions, contributing to biodiversity.	Known for broad genetic diversity, offering greater resistance to pests and diseases.	Reduces the use of pesticides and fertilizers, supporting ecosystem health.	Strengthens local food systems by sharing resilient plant varieties.
Local Adaptation	Seeds collected from local plants are adapted to local climates and soil conditions.	Heirloom varieties are well-suited for specific regional environments, requiring fewer external inputs.	Helps reduce reliance on chemical inputs like fertilizers and pesticides, supporting soil health and reducing pollution.	Promotes the cultivation of region-specific varieties that contribute to food security in diverse climates.
Food Security	Reduces reliance on commercial seed companies, empowering individuals and communities to grow their own food.	Provides a reliable source of seeds that can be saved and replanted season after season.	Reduces the environmental impact of large-scale seed production and transportation.	Seed saving and sharing enhance food availability and reduce dependency on external resources.
Cost Efficiency	Lowers gardening costs by eliminating the need to purchase	Heirloom seeds can be saved and replanted, reducing the need for annual	Low-cost gardening reduces financial barriers, making eco-friendly practices	Communities benefit economically by reducing their reliance on

	seeds each season.	purchases.	more accessible.	industrial agricultural systems.
Preservation of Heritage	Preserves traditional farming practices and contributes to the conservation of unique and rare plant varieties.	Heirlooms represent agricultural heritage and ensure that traditional crops continue to be available for future use.	Conserves genetic resources and maintains plant biodiversity, which is essential for long-term agricultural resilience.	Strengthens cultural ties through the preservation of regional crops and heirloom seed exchanges.
Sustainability	Promotes recycling of plant resources, reducing waste and contributing to eco-friendly practices.	Heirloom varieties help maintain biodiversity, which is essential for sustainable ecosystems and food systems.	Lowers the carbon footprint by minimizing the need for transportation and industrial inputs.	Enhances the resilience of local food systems, making them more sustainable and less dependent on global supply chains.
Heirloom Seed Exchange	Encourages community-based sharing and exchanging of heirloom seeds, promoting biodiversity and gardening self-reliance.	Encourages the exchange of seeds within communities, preserving diverse varieties and promoting ecological gardening.	Reduces the environmental impact of industrial seed production by promoting local, small-scale practices.	Facilitates community-driven food security and environmental stewardship by promoting heirloom varieties and seed saving.

IX. Urban and Small-scale Vegetable Gardening

A. Growing Vegetables in Urban Settings

Urban vegetable gardening has gained popularity as a means to enhance food security, reduce carbon footprints, and create green spaces in densely populated areas. Urban gardening allows city dwellers to grow their own food, even in small spaces, such as balconies, rooftops, or community gardens. This practice not only provides access to fresh, nutritious produce but also promotes sustainable food production by reducing the energy and emissions associated with transporting food over long distances. Urban gardens also contribute to urban biodiversity, improve air quality, and mitigate the urban heat island effect by providing green spaces that absorb heat and carbon dioxide.

B. Space-efficient Gardening Techniques

Space-efficient gardening techniques are essential for maximizing productivity in small urban spaces. Techniques such as square-foot gardening, vertical gardening, and container gardening allow gardeners to grow a variety of crops in limited areas [42]. Square-foot gardening divides the garden into small, manageable sections, enabling intensive planting while minimizing wasted space. Vertical gardening, as discussed earlier, optimizes the use of vertical space, while container gardening provides flexibility and mobility, making it ideal for urban settings where ground space may be scarce. These techniques contribute to the sustainability of urban gardening by increasing food production without requiring large amounts of land or resources.

C. Community Gardens and Shared Gardening Spaces

Community gardens are shared spaces where individuals or groups can grow vegetables, herbs, and flowers. These gardens promote social interaction, provide access to fresh food, and contribute to urban sustainability by converting unused land into productive green spaces. Community gardens foster a sense of community, encourage knowledge sharing, and provide opportunities for individuals who may not have access to their own gardening space to participate in food production [43]. Community gardens often use sustainable practices, such as organic gardening and composting, to reduce their environmental impact and promote biodiversity.

D. Rooftop and Balcony Gardening

Rooftop and balcony gardening are innovative solutions for urban environments where ground space is limited. These gardening techniques utilize underused spaces to grow vegetables, herbs, and even small fruit trees in containers or raised beds. Rooftop gardens, in particular, can provide numerous environmental benefits, including reducing building energy consumption by providing insulation, mitigating stormwater runoff, and improving air quality. Balcony gardening allows individuals to grow their own food, even in apartment buildings or high-rise complexes, contributing to urban food security and sustainability [44]. Both rooftop and balcony gardens support sustainable urban living by creating green spaces that enhance biodiversity and provide access to fresh, local produce.

X. Nutritional and Health Benefits of Sustainable Homegrown Produce

A. Nutritional Superiority of Fresh Produce

Homegrown vegetables harvested at their peak ripeness typically possess higher nutritional value than store-bought produce, which is often picked prematurely and transported long distances. Freshly harvested produce retains more vitamins and minerals because the nutritional quality of vegetables begins to degrade once harvested (Table 2). Research indicates that homegrown vegetables contain higher levels of essential nutrients such as vitamin C, potassium, and antioxidants compared to commercially grown produce. The shorter time between harvest and consumption preserves these nutrients, making homegrown vegetables superior in terms of nutrition. For example, studies have shown that vitamin C levels in spinach and green beans can decrease by 50% within 24 hours of harvesting if not properly stored [45]. Many home gardeners grow heirloom varieties that are often more nutrient-dense than the hybrid varieties selected for commercial farming. Heirloom tomatoes, for example, have been shown to contain higher levels of lycopene, an antioxidant linked to reduced risks of heart disease and cancer,

compared to mass-produced varieties. This nutritional superiority is a significant benefit of sustainable homegrown produce, contributing to healthier diets and overall well-being.

B. Avoidance of Chemical Residues

One of the significant health benefits of sustainable homegrown produce is the avoidance of chemical residues from synthetic pesticides and fertilizers commonly used in conventional farming. Commercially grown vegetables are often treated with pesticides and herbicides to increase yield and manage pests, and these chemicals can leave residues on produce that may pose health risks to consumers [46]. Organic and sustainable gardening practices, on the other hand, rely on natural pest control methods, such as biological controls, composting, and crop rotation, to maintain healthy plants without the use of synthetic chemicals. Homegrown produce, therefore, offers a safer alternative by eliminating exposure to these harmful residues. Consuming organic produce has been associated with a lower risk of exposure to pesticide residues. A study demonstrated that children who consumed organic produce had significantly lower levels of pesticide metabolites in their urine compared to those who ate conventionally grown produce. Avoiding chemical residues is particularly important for vulnerable populations, such as children and pregnant women, who are more susceptible to the potential health effects of pesticide exposure [47].

C. Connection between Sustainable Gardening and Healthy Eating

Sustainable gardening encourages healthy eating habits by fostering a closer connection between individuals and their food sources. Growing vegetables at home promotes a deeper understanding of food production, leading to increased consumption of fresh fruits and vegetables. Studies have shown that individuals who engage in gardening are more likely to consume a higher quantity of vegetables, leading to improved dietary quality. Home gardeners often have access to a diverse range of vegetables, including varieties that may not be available in supermarkets, further contributing to a balanced and nutritious diet. Sustainable gardening practices encourage the use of whole, unprocessed foods, which are associated with numerous health benefits, including reduced risks of chronic diseases such as obesity, diabetes, and cardiovascular disease [48]. By growing their own food, gardeners can control what goes into their diets, avoiding processed foods that are often high in sugar, salt, and unhealthy fats. This connection between gardening and healthy eating is a powerful motivator for individuals seeking to improve their overall health and well-being.

D. Mental and Physical Health Benefits of Gardening

Gardening offers numerous mental and physical health benefits, making it a holistic approach to wellness. The physical activity involved in gardening, such as digging, planting, weeding, and watering, provides a moderate form of exercise that can improve cardiovascular health, strength, and flexibility. Regular physical activity through gardening has been linked to lower body mass index (BMI) and a reduced risk of chronic diseases such as heart disease and type 2 diabetes. Beyond physical health, gardening has been shown to have significant mental health benefits. Engaging with nature through gardening reduces stress, anxiety, and depression, promoting mental well-being [49]. The act of nurturing plants and watching them grow fosters a sense of accomplishment and mindfulness, which can contribute to improved emotional resilience. Gardening also encourages social interaction in community settings, which enhances feelings of connection and reduces loneliness, further contributing to mental health.

Table:2 Nutritional and Health Benefits of Sustainable Homegrown Produce (Source- [45], [46], [48])

Produce Type	Key Nutrients	Health Benefits
Leafy Greens (e.g., Spinach, Kale)	Vitamins A, C, K, Folate, Iron	Supports immune function, promotes healthy vision, aids in blood clotting, and supports cardiovascular health.
Tomatoes	Lycopene, Vitamin C, Potassium, Folate	Reduces the risk of heart disease, improves skin health, and may protect against certain cancers.
Carrots	Beta-carotene, Fiber, Vitamin K1, Potassium	Enhances eye health, supports digestion, and strengthens the immune system.
Peppers (Bell Peppers, Chili Peppers)	Vitamin C, Capsaicin, Vitamin A	Boosts immune health, improves metabolism, and may reduce inflammation and pain.
Berries (Strawberries, Blueberries)	Antioxidants, Vitamin C, Fiber	Promotes heart health, improves brain function, and provides anti-aging benefits.
Herbs (Basil, Mint, Parsley)	Antioxidants, Vitamins A, C, and K	Reduces inflammation, aids digestion, and enhances skin health.
Root Vegetables (Beets, Radishes)	Fiber, Vitamin C, Folate, Potassium	Supports detoxification, lowers blood pressure, and promotes digestive health.
Squash (Zucchini, Pumpkin)	Vitamin A, C, Fiber, Magnesium	Aids in digestion, supports vision health, and enhances immune function.
Legumes (Beans, Peas)	Protein, Fiber, Folate, Iron	Supports muscle growth, improves digestive health, and reduces the risk of heart disease.
Cucumbers	Hydration, Vitamin K, Potassium	Promotes hydration, supports skin health, and aids in weight management.

XI. Challenges in Sustainable Vegetable Gardening

A. Initial Setup Costs and Time Investment

While sustainable gardening offers numerous long-term benefits, the initial setup costs and time investment can be significant barriers for many individuals. Building raised beds, purchasing quality soil, composting materials, organic seeds, and water-efficient irrigation systems can be costly, particularly for those starting from scratch [50]. Setting up a garden requires time for planning, soil preparation, planting, and establishing pest management strategies. The time commitment required for maintaining a garden—watering, weeding, and harvesting—can also be a deterrent for individuals with busy schedules or limited

gardening experience. Overcoming these challenges requires careful planning, resource allocation, and a long-term commitment to sustainable practices.

B. Pest and Disease Management in Organic Systems

Managing pests and diseases in organic gardening systems without the use of synthetic pesticides presents a significant challenge for sustainable gardeners. Organic pest control relies on preventive measures, such as crop rotation, companion planting, and biological controls, which can be less immediately effective than chemical pesticides [51]. Certain pests, such as aphids, slugs, and caterpillars, can cause substantial damage to crops if not managed effectively. Organic gardeners must be vigilant in monitoring pest populations and employing environmentally friendly control methods, such as introducing beneficial insects, using neem oil, or applying homemade repellents.

C. Lack of Knowledge and Resources

A lack of knowledge and resources can also hinder the adoption of sustainable vegetable gardening practices. Many individuals may be unfamiliar with organic gardening techniques or unsure of how to implement sustainable practices such as composting, crop rotation, or rainwater harvesting. Access to resources, such as organic seeds, composting materials, and gardening tools, may be limited, particularly in urban or low-income areas. Furthermore, educational resources on sustainable gardening may not be readily available or accessible to all, making it difficult for novice gardeners to succeed [52]. Addressing these challenges requires increased access to gardening education and resources through community programs, extension services, and online platforms.

D. Climate and Soil Constraints in Different Regions

Climate and soil conditions vary widely across regions, posing challenges for sustainable vegetable gardening. In arid or drought-prone areas, water scarcity can limit the success of gardens, requiring the use of water-efficient practices such as drip irrigation, mulching, and drought-resistant plant varieties. In contrast, regions with heavy rainfall may struggle with soil erosion, waterlogged soils, and fungal diseases. Soil quality also varies, with some regions having poor or contaminated soils that require significant amendments to support healthy plant growth [53]. Sustainable gardeners must adapt their practices to suit local climate and soil conditions, which may require additional investments in soil improvement, irrigation, and pest management.

XII. Future Trends and Innovations in Sustainable Vegetable Gardening

A. Technological Innovations for Sustainability

Technological advancements are transforming sustainable vegetable gardening by introducing new tools and techniques that improve efficiency, reduce resource use, and enhance crop productivity. One such innovation is the development of smart irrigation systems that use sensors to monitor soil moisture levels and deliver water precisely when and where it is needed. These systems can significantly reduce water waste, making them ideal for regions facing water scarcity. Similarly, advances in LED grow lights and energy-efficient greenhouse technologies allow for year-round vegetable production in controlled environments, reducing the reliance on external climate conditions. Another promising innovation is the use of biochar, a carbon-rich material produced from organic waste, which can improve soil fertility,

increase water retention, and sequester carbon [54]. Biochar has been shown to enhance plant growth and reduce the need for synthetic fertilizers, making it a valuable tool for sustainable gardening. These technological innovations are paving the way for more sustainable and efficient vegetable gardening practices.

B. Role of Automation and Smart Gardening Tools

Automation and smart gardening tools are becoming increasingly popular in sustainable gardening, offering solutions that reduce labor, optimize resource use, and improve plant care. Robotic systems for tasks such as weeding, planting, and watering are being developed to assist gardeners in maintaining their gardens more efficiently [55]. For example, robotic weeders use machine learning algorithms to identify and remove weeds without disturbing crops, reducing the need for chemical herbicides. Automated irrigation systems can be programmed to water plants at optimal times, conserving water and ensuring consistent plant growth. Smart gardening tools, such as soil sensors and plant health monitoring devices, provide real-time data on soil conditions, nutrient levels, and plant health, allowing gardeners to make informed decisions about fertilization and pest management. These tools contribute to the sustainability of gardening by optimizing resource use and minimizing environmental impacts.

C. Expansion of Urban Farming Initiatives

Urban farming initiatives are gaining momentum as cities recognize the environmental, social, and economic benefits of growing food locally [56]. Urban agriculture can contribute to food security, reduce the carbon footprint associated with transporting food, and create green spaces that enhance biodiversity and mitigate the urban heat island effect. Vertical farming, rooftop gardens, and community gardens are among the many forms of urban farming that are being integrated into city planning to promote sustainable food systems. These initiatives often involve collaborations between local governments, non-profit organizations, and community groups to provide resources and education to urban residents, empowering them to grow their own food.

D. Sustainable Gardening in a Post-Pandemic World

The COVID-19 pandemic has spurred a resurgence in home gardening, as people sought ways to grow their own food during periods of uncertainty and supply chain disruptions. This shift has highlighted the importance of local food production and self-sufficiency in building resilient food systems [57]. In a post-pandemic world, sustainable gardening is likely to continue growing in popularity as individuals and communities recognize its value for enhancing food security, promoting environmental sustainability, and improving physical and mental health. The lessons learned during the pandemic have underscored the need for decentralized, sustainable food systems that can withstand future crises and disruptions.

Conclusion

Sustainable vegetable gardening offers a multitude of benefits, from providing nutrient-rich, chemical-free produce to promoting environmental stewardship and supporting mental and physical health. While initial costs and knowledge barriers pose challenges, the adoption of organic practices, efficient resource use, and innovative technologies can make gardening more accessible and efficient. Urban farming initiatives, seed saving, and climate-resilient practices further contribute to the long-term sustainability of food systems, particularly in a post-pandemic world where self-sufficiency and local food production

have gained importance. As smart tools and automation continue to evolve, the future of sustainable gardening looks promising, offering scalable solutions for both small-scale home gardeners and larger urban communities.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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