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Review

Soilless Agricultural Systems: Opportunities, Challenges, and Applications for Enhancing Horticultural Resilience to Climate Change and Urbanization

Imran Ali Lakhiar [1], Haofang Yan [1,*], Tabinda Naz Syed [2], Chuan Zhang [3], Sher Ali Shaikh [4], Md. Rakibuzzaman [1,5] and Rahim Bux Vistro [4]

1 Research Center of Fluid Machinery Engineering and Technology, Jiangsu University, Zhenjiang 212013, China; 5103160321@stmail.ujs.edu.cn (I.A.L.)
2 College of Engineering, Nanjing Agricultural University, Nanjing 210031, China
3 School of Agricultural Equipment Engineering, Jiangsu University, Zhenjiang 212013, China
4 Faculty of Agricultural Engineering, Sindh Agriculture University, Tandojam 70060, Pakistan
5 Department of Mechanical Engineering, International University of Business Agriculture and Technology, Dhaka 1230, Bangladesh
* Correspondence: yanhaofangyhf@163.com

Abstract: Rapid urbanization, climate variability, and land degradation are increasingly challenging traditional open-field farming systems. Soilless farming (SLF) has emerged as a complementary approach to enhance horticultural resilience in space-constrained and climate-stressed environments. This review critically evaluates the role of SLF within the broader framework of climate-smart agriculture (C-SA), with a particular focus on its applications in urban and peri-urban settings. Drawing on a systematic review of the existing literature, the study explores how SLF technologies contribute to efficient resource use, localized food production, and environmental sustainability. By decoupling crop cultivation from soil, SLF enables precise control over nutrient delivery and water use in enclosed environments, such as vertical farms, greenhouses, and container-based units. These systems offer notable advantages regarding water conservation, increased yield per unit area, and adaptability to non-arable or degraded land, making them particularly relevant for high-density cities, arid zones, and climate-sensitive regions. SLF systems are categorized into substrate-based (e.g., coco peat and rock wool) and water-based systems (e.g., hydroponics, aquaponics, and aeroponics), each with distinct design requirements, nutrient management strategies, and crop compatibility. Emerging technologies—including artificial intelligence, the Internet of Things, and automation—further enhance SLF system efficiency through real-time data monitoring and precision control. Despite these advancements, challenges remain. High setup costs, energy demands, and the need for technical expertise continue to limit large-scale adoption. While SLF is not a replacement for traditional agriculture, it offers a strategic supplement to bolster localized food systems and address climate-related risks in horticultural production. Urban horticulture is no longer a peripheral activity; it is becoming an integral element of sustainable urban development. SLF should be embedded within broader resilience strategies, tailored to specific socioeconomic and environmental contexts.

Keywords: aeroponics; aquaponics; climate-smart agriculture technology; hydroponics; substrate culture; urban farming; vertical farming; water culture

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1. Introduction

Global food systems are under increasing pressure from the compounded effects of climate change, declining freshwater availability, rapid urbanization, and continued population growth. These interconnected challenges are reshaping the environmental and socioeconomic conditions traditionally supporting the agriculture sector, prompting the need for innovative and context-specific responses. As these pressures intensify, they manifest at the farm level in increasingly unpredictable ways, affecting growing seasons, water supply, and overall system reliability. Consequently, conventional open-field farming—heavily reliant on stable agro-ecological conditions—is now frequently disrupted by the rapid, erratic rainfall, land degradation, and rising temperatures [1–4]. Zhai et al. [5] stated that the planet's average temperature has increased by 1.1 °C since the beginning of the Industrial Era. To keep global warming below 2 °C, gas emissions must be reduced by 25% by 2030. Additionally, the depletion of freshwater resources is accelerating due to population growth, urbanization, and the increasing demands of industry, coupled with climate change, due to these human activities. As global demand for freshwater rises, its availability is increasingly compromised, with many regions experiencing more frequent droughts and reduced rainfall. Overextraction of groundwater and pollution further exacerbate the problem, leaving many areas facing severe water shortages. As a result, freshwater ecosystems are under stress, and access to clean water for agriculture and drinking is becoming more limited. Besides, a decrease in freshwater availability and seawater warming is expected to have a catastrophic effect on phytoplankton, which produce approximately four-fifths of global photosynthesis and consume atmospheric CO_2. To address the growing issues of global warming, we must now change our habits by implementing climate resilience tools [6–9].

At the same time, urbanization is rapidly altering spatial dynamics and food demand. According to the United Nations [10], the global urban population has surged from 13% in 1900 to over 57% in 2020 and is expected to approach 70% by 2050. This demographic shift is especially pronounced in developing countries, where industrialization, policy initiatives, and infrastructure expansion drive urban growth. China exemplifies this trend, with its urbanization rate rising from 10.64% in 1949 to 66.16% by the end of 2023 [11]. Moreover, in numerous countries, arable land is being rapidly converted into commercial and residential developments, particularly in metropolitan regions, substantially diminishing the area available for food production. These changing land-use patterns and shifting lifestyle preferences intensify the demand for diverse, high-quality agricultural products. As more people migrate to cities, demands for diverse, reliable, and nutritious food intensify, exerting pressure on supply chains and natural resources [12–14]. The combined effects of reduced arable land and surging urban food demand necessitate rethinking where and how crops are grown.

In this context, urban agriculture is increasingly seen as a complementary strategy to strengthen local food access. While the term "urban agriculture" is broadly used in the literature to describe food production activities in and around cities, this review adopts a more focused interpretation aligned with horticultural production, specifically cultivating high-value, short-cycle crops through soilless farming (SLF) systems. SLF is a practical tool for advancing sustainable, space-efficient, and climate-resilient urban horticulture. In particular, SLF systems present a promising approach. By decoupling plant production from the soil, SLF technologies—including water-based and substrate-based methods—enable precise nutrient delivery, minimize water losses, and support crop cultivation in non-traditional spaces such as rooftops, vertical structures, and retrofitted urban environments [15–21].

SLF has thus gained recognition as a key component of climate-smart agriculture (C-SA), particularly in areas where conventional soil-based practices are unviable. While not a universal substitute for traditional agriculture, SLF holds considerable potential in arid, degraded, or space-limited settings where high-value horticultural crops can be cultivated with improved water-use efficiency and reduced environmental impact. Although Chopra et al. [22] suggested SLF is gaining traction globally, current adoption remains limited. Of the approximately 1.6 billion hectares of global cropland, only around 95,000 hectares are under SLF systems, accounting for just 3.5% of total crop production. Traditional agriculture dominates food production, particularly in rural and large settings. In contrast, SLF is more applicable in urban, peri-urban, or resource-constrained areas where land availability and environmental stability are limited. Gruda et al. [23] reported that SLF systems in the Netherlands achieved up to 50% reductions in water and fertilizer use, with improved control over vegetative and generative crop growth phases. Martinez-Mate et al. [24] found that lettuce cultivation using the nutrient film technique in southeastern Spain required 62% less water than comparable soil-based production. NASA [25] noted that aeroponics can reduce water use by up to 99%, nutrient requirements by 50%, and crop cycles by 45%. Overall, SLF systems may reduce irrigation needs by 50–95% compared to conventional open-field farming. These savings largely stem from recirculating irrigation systems that minimize water loss through evaporation and runoff, especially in closed-loop setups in modern greenhouses and vertical farms [26–30]. However, it is critical to recognize that such efficiencies represent ideal scenarios. Real-world performance depends on numerous variables, including system design, crop species, climate conditions, and management practices. For growers transitioning from traditional greenhouse or partially soilless systems, efficiency gains may vary significantly depending on their current operational baseline and level of technological integration.

Despite increasing interest, comprehensive reviews of SLF's role in addressing climate change and urban food security remain limited, especially in sustainable horticultural production. Therefore, this study addresses that gap by systematically evaluating SLF systems' potential, challenges, and prospects within urban horticulture. The primary motivation for this review stems from the urgent need to ensure resilient, productive, and sustainable food systems in the face of accelerating environmental pressures. By framing SLF as a targeted adaptation strategy, this paper critically explores its applications, limitations, and contributions to localized food resilience. Based on these aims, the study addresses the following research questions:

(1) What is climate resilience within the context of global climate change and agricultural adaptation?
(2) How do soilless farming systems improve water-use efficiency and crop productivity in resource-limited environments?
(3) What are SLF systems' key types and design principles, and how do they differ in nutrient management, crop compatibility, and infrastructure needs?
(4) How can SLF technologies support sustainable horticultural production in urban and peri-urban areas?
(5) What are the current limitations, opportunities, and research gaps for SLF at global and regional levels, particularly in China?
(6) How do digital tools (e.g., AI and IoT) enhance SLF systems' functionality, scalability, and sustainability?

While this review occasionally uses the broader term "agriculture", its scope is explicitly limited to horticultural production systems, particularly those adapted to urban and peri-urban environments. The strategies and technologies discussed, including SLF methods such as water culture and substrate culture, are not intended for extensive field crops but for space-constrained, climate-vulnerable regions where traditional open-field farming is less feasible. While climate resilience is widely explored across diverse agricultural systems, this review focuses on SLF within the horticultural sector. These systems, discussed in detail in later sections, align with climate-resilient principles but are best suited for high-value, short-cycle crops. This contextual clarification ensures that the conclusions drawn are appropriately framed and not generalized to all forms of agriculture. However, the manuscript's structure is as follows: Section 2 outlines the methodological framework used in the review. Section 3 presents the key findings and thematic analysis structured around the research questions. Section 4 provides the conclusion and policy-relevant recommendations derived from the study.

2. Methodology

To investigate the role of SLF in C-SA, we conducted a systematic review of peer-reviewed literature focused on soil-based and soilless cultivation systems. The search was guided by defined inclusion and exclusion criteria to ensure scientific relevance and clarity. Keywords such as "climate resilience", "soilless farming", "substrate culture", "hydroponics", "aquaponics", "aeroponics", and "precision horticulture" were used across major academic databases, including Web of Science, Scopus, and Google Scholar.

As of 20 May 2025, we compiled a dataset of 299 relevant publications. From each source, we extracted key metadata (title, keywords, abstract, and references) to facilitate thematic analysis and comparative insights. Figure 1 presents a flowchart summarizing this study's review process and methodological framework.

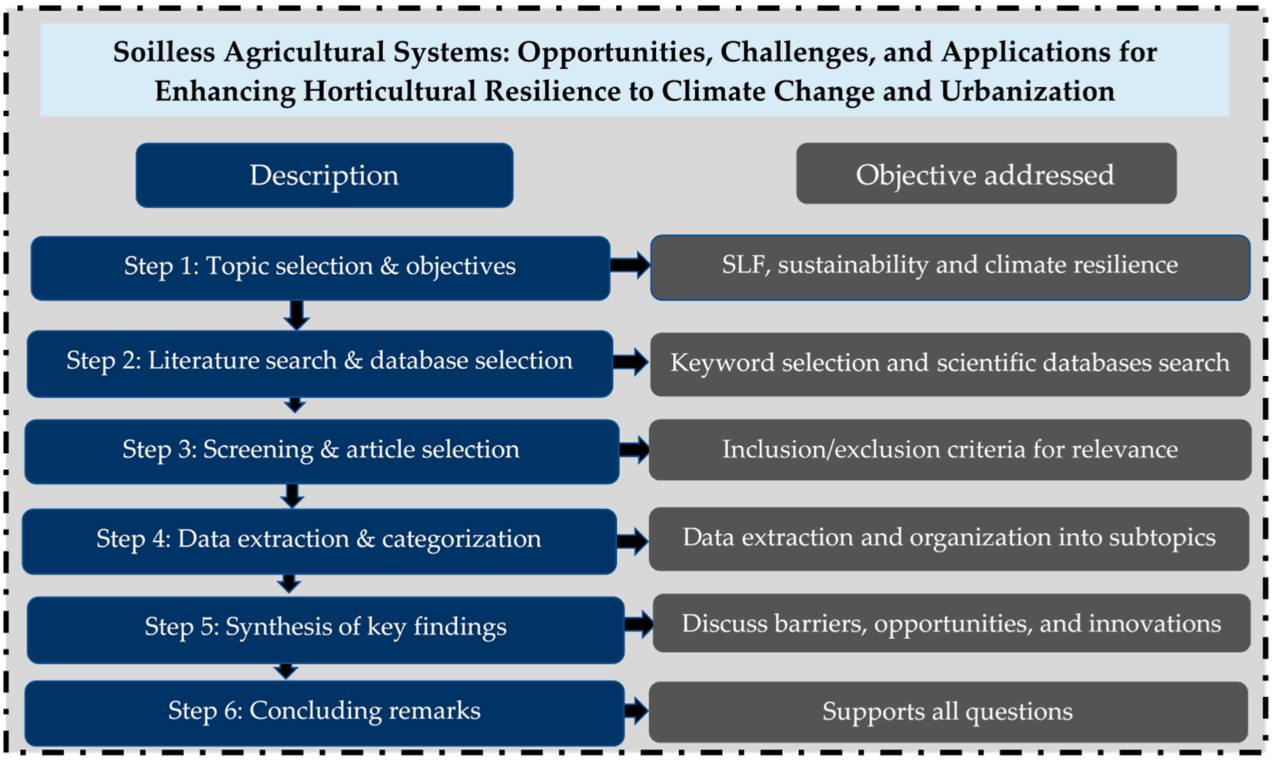


Figure 1. Review methodology.

3. Results and Discussion

This section presents the core insights from the reviewed literature, addressing the research questions outlined earlier. The findings highlight the evolving role of SLF technologies within climate-smart agriculture, focusing on their applications in urban and climate-vulnerable settings. Each subsection below explores specific dimensions of SLF, comparing system designs, evaluating their effectiveness, and discussing practical implications for sustainable horticultural production.

3.1. What Is Climate Resilience Within the Context of Global Climate Change and Agricultural Adaptation?

Climate change, driven by rising greenhouse gas emissions from industrial activity, energy consumption, and land-use changes, has intensified global warming and disrupted hydrological cycles. These disruptions have led to greater climate variability, marked by erratic rainfall, extreme weather events, prolonged droughts, and shifting temperature patterns. In this context, building climate resilience has become a core strategy in C-SA. The term "resilience" refers to the capacity of systems—be they ecological, socioeconomic, or technological—to absorb and recover from disturbances while maintaining core functions. In agricultural contexts, climate resilience implies the ability of food systems to anticipate, adapt to, and recover from climate-induced shocks while sustaining productivity, resource efficiency, and ecological balance. Resilience is achieved through interconnected practices and policies rather than a single intervention. These include integrating C-SA technologies, strengthening institutional frameworks, and promoting innovations in resource management [9,18,31,32]. Figure 2 presents a flowchart detailing how climate-resilient strategies can be achieved by integrating sustainable technologies and practices.

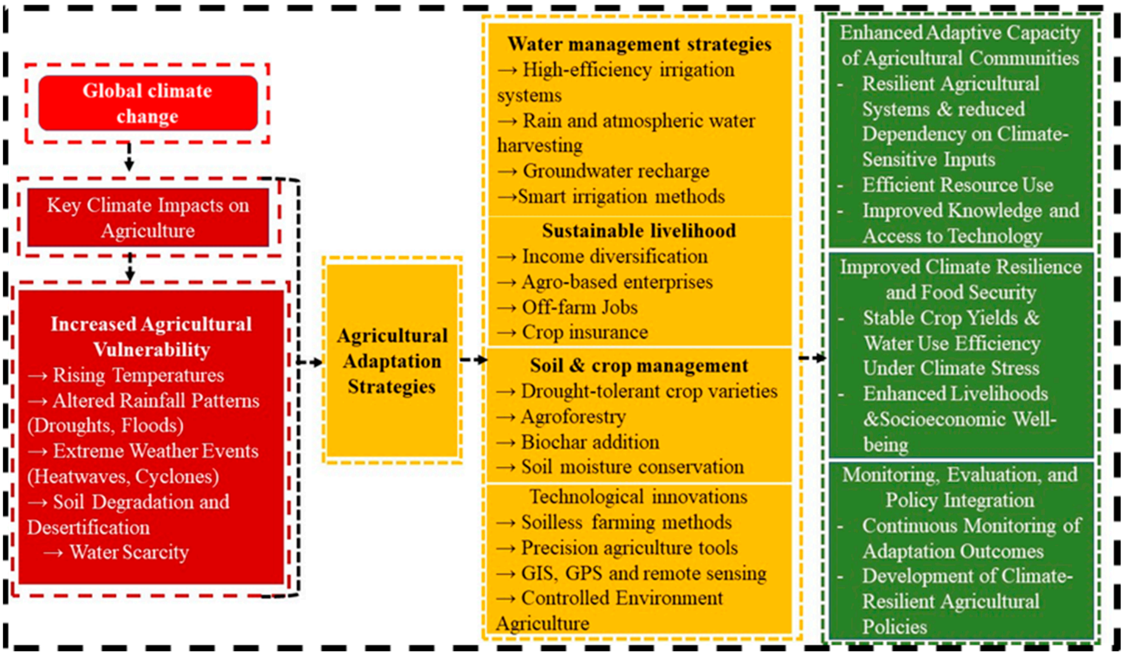


Figure 2. Flowchart showing the integration of technology and sustainable practices to enhance agricultural adaptation and climate resilience.

In agriculture, resilience-building strategies involve various adaptive approaches [33]. These range from adopting efficient irrigation systems and drought-resilient cropping techniques to enhanced decision-making tools using remote sensing and climate forecasting models. Promoting agroecological principles, community-based resource management, and diversified farming systems can also buffer production against unpredictable weather events. The Food and Agriculture Organization [34] and other international agencies continue advocating for integrative models that blend technology, local knowledge, and institutional support. Importantly, resilience is not only about surviving stress but also about transforming practices for long-term sustainability. Implementing targeted, data-driven, and context-specific solutions—including soilless farming systems discussed in the following sections—is crucial in increasing food system flexibility, especially in space-limited and climate-vulnerable environments.

In summary, climate resilience in agriculture is a dynamic and multi-dimensional process. It involves anticipating climatic risks, reducing vulnerabilities, and creating adaptive capacity through innovation, planning, and cooperation [35–37]. As shown in Figure 2, combining technological advancements with sustainable land and water management practices forms a vital pathway for strengthening agricultural systems in the face of climate uncertainty.

While the above strategies offer a broad framework for agricultural adaptation, they must be tailored to specific production systems. In space-constrained urban environments, horticultural resilience must take a different path and not depend on arable land or stable field conditions. This is where SLF systems become highly relevant. By decoupling food production from soil and enabling precision resource management, SLF aligns with the principles of climate resilience. These systems offer a context-specific solution for high-value horticultural crops grown in controlled environments, especially in urban and peri-urban areas where traditional agriculture is no longer viable. Hence, while the discussion above addresses resilience at a general agricultural level, this review focuses on SLF as a practical, scalable, and climate-responsive tool for strengthening horticultural resilience in the face of environmental and demographic pressures.

3.2. Traditional Farming and Soilless Farming Systems

Traditional farming systems generally refer to agricultural practices based on open-field, soil-based cultivation, where crops are grown directly in the natural environment without significant technological intervention. These systems are highly dependent on local climate conditions, rainfall patterns, and the natural fertility of the soil [38]. Irrigation, when used, typically involves surface or furrow methods, leading to considerable water losses due to evaporation, runoff, and inefficient distribution. In traditional settings, farming inputs such as fertilizers and pest control measures are often applied broadly, leading to potential environmental impacts, such as soil degradation, nutrient leaching, and increased greenhouse gas emissions. While greenhouse farming and polytunnel structures have been introduced in some regions, they are often only partially climate-controlled, offering protection against extreme weather but not providing complete environmental optimization [39–41].

SLF systems provide a context-specific cultivation strategy that differs from traditional soil-based methods and may serve as an alternative in environments where conventional farming methods are limited by resource or environmental constraints. These systems grow plants without natural soil. SLF methods are typically implemented within controlled environment agriculture systems, such as advanced greenhouses and vertical farms, where temperature, humidity, light, and nutrient supply are tightly managed to optimize plant development [17]. In this study, "traditional farming" refers to open-field, soil-based cultivation without artificial climate control, where environmental fluctuations directly affect crop performance. While these systems face growing challenges such as water inefficiency and climate sensitivity, SLF offers targeted solutions in contexts where traditional methods are less viable. Table 1 provides a comparative overview of SLF benefits under these specific conditions.

Table 1. Key differences between SLF and traditional farming systems [42–45].

Feature	Soilless Farming	Traditional Farming
Growing medium	Nutrient solution and substrate media	Soil
Water consumption	50 to 95% less water usage (if properly managed) and 5–10% wastage of water (due to water quality, salt buildup, and occasional system flushing)	Significantly higher water usage and wastage
Space efficacy	Occupied the lower space	Requires more horizontal land space

Table 1. *Cont.*

Feature	Soilless Farming	Traditional Farming
Crop variety selection	Recommended for leafy vegetables	Unlimited access to crop selection and a wide variety of crops suited to the local climate
Nutrient control	Precise nutrient control tailored to plant needs	Mainly depends on soil quality
Pest and disease	Reduced risk of soilborne pests and diseases	Higher risk of pests, diseases, and weeds
Climate impact	Lower overall environmental impacts	Higher environmental impact
Setup cost	High initial setup (equipment, infrastructure)	Lower initial cost (depends on land and tools)
Labor requirements	Requires specialized knowledge	More manual labor needed for planting, irrigation, and harvesting
Climate dependency	Less dependent on external climate conditions	Highly reliant on weather and climate
Yield and efficiency	Higher yields per square meter	Depending on climate and soil conditions
Crop growth speed	Faster growth	Slower growth
Maintenance	Regular monitoring and adjustments to nutrient solutions	Regular tilling, fertilization, irrigation, and pest control
Energy use	Requires more energy (60–90% for heating and cooling, 10–30% for lighting, and 5–10% for pumps) and varies depending on type, area, and technologies used	No external energy required for heating, cooling, and lighting
Sustainability	Using less land and water is more sustainable, especially in urban areas (spaces like rooftop gardens, indoor farms, green walls, etc.).	Sustainability depends on practices (e.g., crop rotation and conservation)

3.3. How Does Soilless Farming Improve Water-Use Efficiency and Crop Productivity as a Measure of Climate Resilience?

Traditional open-field agriculture continues to form the backbone of global food systems, especially in rural and large-scale production settings. However, these systems are increasingly constrained by land degradation, erratic weather, and water scarcity. In contrast, SLF has gained attention as a viable method for intensifying food production in urban and resource-limited environments, particularly for horticultural crops. These systems are typically operated in controlled environments like vertical farms, rooftop greenhouses, or climate-controlled indoor units, allowing for consistent production unaffected by external climate variability [20–23].

Several studies have reported that SLF technologies can reduce water waste, minimize postharvest losses, and limit the spread of soilborne pests and diseases [46–48]. These benefits are particularly valuable for high-value, short-cycle horticultural crops such as leafy greens and tomatoes. Higher water-use efficiency is a defining advantage of SLF against open farming systems. A study by Gruda [49] informed that field-grown tomatoes may require up to 200 $\pm$ 100 L of water per kilogram of produce. At the same time, SLF systems in controlled environments may reduce this to 14–20 L/kg through closed-loop irrigation and evaporative recovery. Besides saving water, SLF systems are well suited for space-constrained settings. Rooftops, unused urban plots, and indoor spaces can be transformed into productive growing areas without requiring fertile land. Though initial infrastructure costs are high, the yield per unit area return, local food security, and reduced transportation emissions can justify the investment in dense urban contexts [50,51]. Significantly, SLF systems contribute to a lower environmental footprint. By reducing the use of pesticides and enabling localized food production, SLF decreases both chemical runoff and greenhouse gas emissions from extended supply chains [52–55].

Given their adaptability to enclosed environments, SLF systems are most suitable for horticultural production rather than large-scale cereal farming. Leafy greens, microgreens, strawberries, and herbs are among the most responsive crops to SLF methods, particularly under urban conditions where land, water, and climate stability are constrained. These crops also hold higher market value and shorter growth cycles, making them ideal candidates for controlled-environment agriculture. Therefore, the resilience benefits of SLF—particularly in water savings, spatial efficiency, and yield optimization—are most meaningfully realized in horticultural systems aligned with urban sustainability and food access goals [56].

In conclusion, SLF should not be viewed as a complete replacement for traditional agriculture but rather as a strategic and context-specific solution to enhance horticultural resilience under climate and urban pressures. Integrated into a diversified C-SA framework, SLF offers a promising pathway toward sustainable food systems in the twenty-first century. Table 2 discusses some studies that compared water usage between soil and SLF systems. However, some of the key advantages are discussed in the sections below.

Table 2. Comparison of water usage (WU) and yield between soil and SLF systems.

Crop Type	AR	TFS	WU	SLF	WU	YD	Ref.
Sweet pepper	Egypt	SS	312.5 L/m^2/s	SC, MP, & PC	199.6, 269, & 233.2 L/m^2/s	SC (12.7%) +, MP (4.6%), & PC (16.2%) −	[57]
Zucchini squash	Italy	N/M	256 L/m^2/s	PC, CF, & PM	200, 221, & 185 L/m^2/s	PC (33.5%), CF (20.3%), & PM (32.6%) +	[58]
Lettuce	USA	N/M	250 ± 25 L/kg/y	NFT	20 ± 3.8 L/kg/y	11 times +	[59]
Basil	UAE	Soil pots	N/M	AQP	N/M	+ in AQP	[60]
Tomatoes	Saudi Arabia	N/M	HWC	LC	50% −	− in LC	[61]
Lettuce	Palestine	N/M	HWC	VT, PMP, & NFT	SLF systems saved up 94% to 123%	No significant variation observed	[62]
Tomatoes	Turkey	N/M	87.4 (PE) & 102.9 (GE) L plant^{-1}	DWC & RW	41.7 (PE), 48.6 (GE), 70.34 (PE), and 92.5 (GE) for DWC & RW	No significant variation observed	[63]
Mulberry Cutting	China	N/M	HWC	ARP	Less water	Highest gains in root growth, survival, and biomass with ARP	[64]
Onion	India	N/M	More water	DWC	Less water	2 times +	[65]

Note: TFS is a traditional farming system, AR is the area, N/M is no any method mentioned, NFT is the nutrient film technique, SS is the sandy soil, SC is rice straw culture, MP is modified plant plane hydroponic, PC is the perlite culture, + is increased, − is decreased, CF is cocofiber, PM is pumice, and AQP is the aquaponics. LC is local gravel, peat moss, humin-substrate, and perlite in a 4:3:1.5 ratio. HWC is higher water consumption, YD is the yield difference, PE is the polytunnel experiment (2018), GE is the glasshouse experiment (2019), RW is rockwool, ARP is the aeroponically rapid propagation with temp/humidity regulation, DWC is the deep water culture, and MPC is a 1:1 ratio of perlite and cocopeat. VT is a pure volcanic tuff, and PMP is the peat moss–perlite mixture (2:1 v/v). The information provided here is for reference purposes only, and actual water usage may vary depending on various factors.

3.3.1. Water Conservation

SLF systems use water much more efficiently than traditional soil-based methods. These systems recirculate water, giving plants the precise amount needed for growth and reducing waste. This is particularly crucial in water-scarce areas, allowing food production with significantly less water. However, while SLF systems are water-efficient, regular monitoring and maintenance are necessary to ensure the water and nutrient solutions remain balanced [15–17].

Solution: Implementing automated monitoring and control systems can help maintain optimal water quality and minimize water waste, ensuring long-term efficiency and sustainability.

3.3.2. Reduced Land Use and Soil Degradation

SLF systems can be utilized in urban environments like vertical farms and areas with poor soil quality, allowing for food production where traditional agriculture is not feasible. This reduces the demand for arable land and prevents soil degradation, deforestation, and biodiversity loss. However, establishing SLF systems requires significant initial investments and infrastructure [51,66].

Solution: To mitigate high setup costs, promoting government subsidies, financial incentives, or partnerships with private companies can help make SLF systems more accessible to farmers, particularly in urban areas. While the land prices in urban areas are typically higher, SLF systems, such as vertical farming and indoor hydroponics, require significantly less land than traditional soil-based farming. These systems can be implemented in underutilized spaces such as rooftops, vacant lots, and abandoned buildings, which reduces the need for large tracts of arable land. Despite the higher initial setup costs, SLF systems offer the advantage of local food production, improving food security and reducing the costs and emissions associated with food transportation.

3.3.3. Minimized Pesticides and Herbicides Use

SLF systems provide precise nutrient delivery, which helps reduce nutrient runoff, a common issue in traditional farming. This precise management also means there is generally less need for herbicides and pesticides because the controlled environment naturally limits the conditions leading to pest and disease problems. However, the effectiveness of pest and disease control in SLF systems is still dependent on proper climate management. In well-controlled systems, the risk of pests and fungi is lower, but challenges can still arise, particularly in closed systems. As a result, disease management remains essential, and proper climate regulation is crucial to keep pests and diseases under control [67].

Solution: Implementing integrated pest management techniques and using beneficial microorganisms or biocontrol agents can reduce pesticide use, maintain a hygienic environment, and maintain plant health in soilless systems.

3.3.4. Higher Crop Yields and Faster Growth

In SLF, water, nutrients, and climate factors are precisely controlled, leading to faster growth and higher yields than traditional farming methods. This efficiency allows more food to be produced in less time and supports year-round production. A limitation of SLF, however, is the dependency on precise environmental controls and the need for technical expertise in system management [68,69].

Solution: To overcome this challenge, extensive training programs for growers and the development of user-friendly automated systems can ensure the successful and consistent management of SLF systems.

3.3.5. Reduced Environmental Footprint

SLF, particularly in urban areas, can reduce the need to transport food from rural farms to cities, decreasing the carbon footprint associated with food distribution. Additionally, by growing food locally, SLF systems can reduce the energy consumption and greenhouse gas emissions of large-scale conventional farming. A potential drawback is the energy demand of specific SLF systems, such as artificial lighting in vertical farms [70,71]. SLF systems, especially in vertical farming, are energy-efficient when integrated with renewable energy sources. However, energy costs can be significant, particularly for indoor system lighting [72].

Solution: Integrating renewable energy sources like solar or wind power into SLF systems can significantly reduce their energy consumption and carbon footprint. LED lighting and energy-efficient climate control systems can reduce energy demand. While LED lighting requires electricity, it is substantially more energy-efficient than traditional lighting systems. LEDs consume much less power while providing optimal light conditions for plant growth, making them an effective solution for reducing overall energy use in SLF systems. Additionally, integrating renewable energy sources like solar or wind power further enhances the sustainability of SLF systems by reducing their reliance on non-renewable energy and lowering their carbon footprint.

3.3.6. Waste Minimization and Resource Recycling

SLF systems are inherently sustainable because they recycle water and nutrients, minimizing waste and reducing environmental impacts. For example, in aquaponics, fish waste provides a nutrient-rich source for plants, helping to close the loop in nutrient cycling. However, despite this sustainability, waste disposal, especially in systems with high-density production, can still be a concern, as high concentrations of nutrients like sodium can negatively impact plant health [73]. While aquaponics offers a sustainable way to recycle nutrients, it requires careful nutrient management to balance fish waste with the plants' nutritional needs. Since fish waste may not supply sufficient potassium levels, supplemental fertilization may be necessary to adjust nutrient levels, ensuring optimal plant growth and yield. This careful management of nutrient levels is crucial for maintaining plant health and system productivity.

Solution: Effective waste management strategies are essential to further enhance the sustainability of SLF systems. These can include composting, vermiculture, and organic waste recycling to produce energy. By integrating these methods, SLF systems can significantly reduce waste generation, promote resource efficiency, and close nutrient loops.

However, these benefits are not universal; they are conditional on appropriate system design, crop selection, and access to technical knowledge. SLF systems often require significant up-front investment and operational oversight, especially in hydroponic and aeroponic setups that rely on precise environmental control. Therefore, SLF is best positioned as a complementary tool for sustainable horticultural production, particularly in urban and peri-urban settings, rather than as a solution for broad-acre field crops. With proper support, innovation, and planning, SLF can contribute meaningfully to developing adaptive and resilient food systems under changing climatic and demographic conditions.

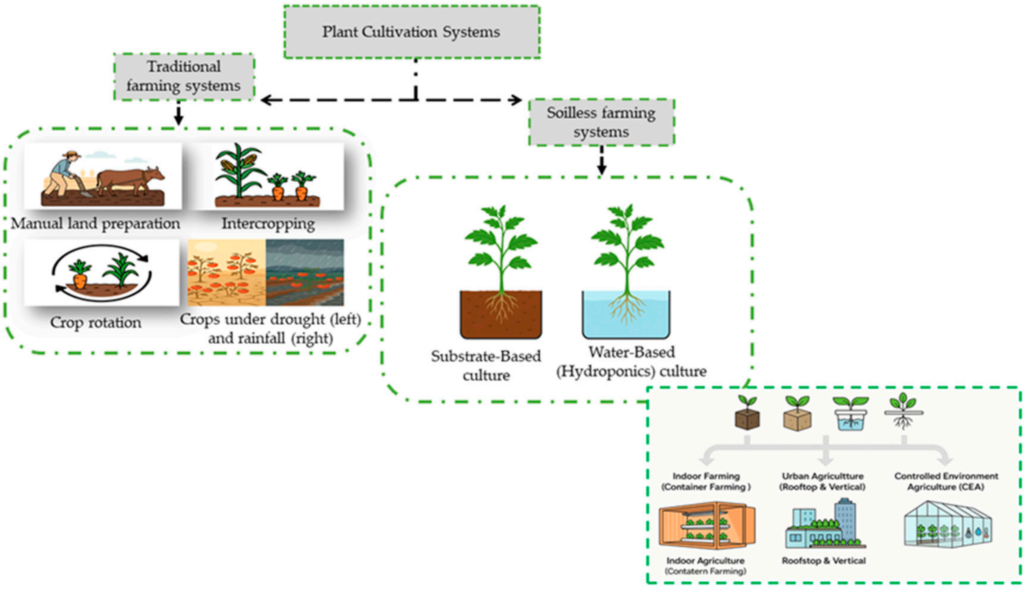
3.4. What Are SLF Systems' Key Types and Design Principles, and How Do They Differ in Nutrient Management, Crop Compatibility, and Infrastructure Needs?

3.4.1. Types of Soilless Farming

Currently, SLF is intensively used in greenhouses to enhance control over the growing environment and mitigate uncertainties in the water and nutrient status of the soil. It is an artificial means of providing plants with support and a reservoir for nutrients and water. The classification of SLF is based on several factors, including the type of substrate and container used, how the nutrient solution is delivered to the plants—whether through flowing, stagnant, or mist nutrient solution cultures—and the handling of the drainage nutrient solution, which can be categorized as open (free-draining) or closed (recirculating) systems. Generally, there are two primary types of SLF systems [see Figure 3]: (1) substrate culture and (2) water culture [17].

Substrate-Based Culture

The substrate farming system involves cultivating crops in a solid, non-soil medium that may be inert (e.g., perlite and stonewool) or organic (e.g., coir and peat moss), without using natural soil. These naturally derived or industrially processed materials provide mechanical support for plant roots in containers, grow bags, or trays. While most substrate materials do not supply significant nutrients on their own, they serve as a physical support medium, and all essential nutrients are provided through nutrient solutions. Moreover, the substrate culture is further categorized as open or closed irrigation systems. In an open irrigation system (e.g., drip, etc.), the nutrient solution is applied to the upper surface of the substrate in a bench or pot, and any excess solution is allowed to drain from the bottom of the container into the environment. In contrast, a closed irrigation system is one in which the nutrient solution is actively collected, recirculated, and reused after draining from the root zone. These systems are designed to reduce water and nutrient losses while enabling more precise control over nutrient delivery [74,75].



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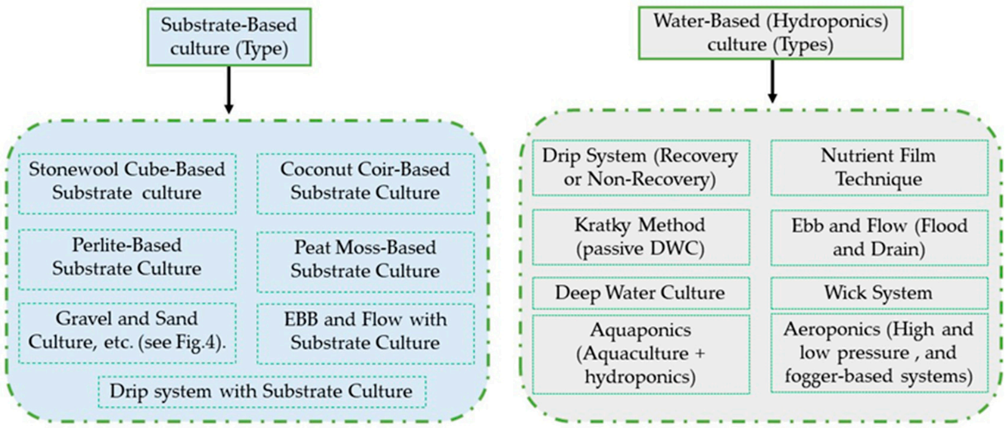

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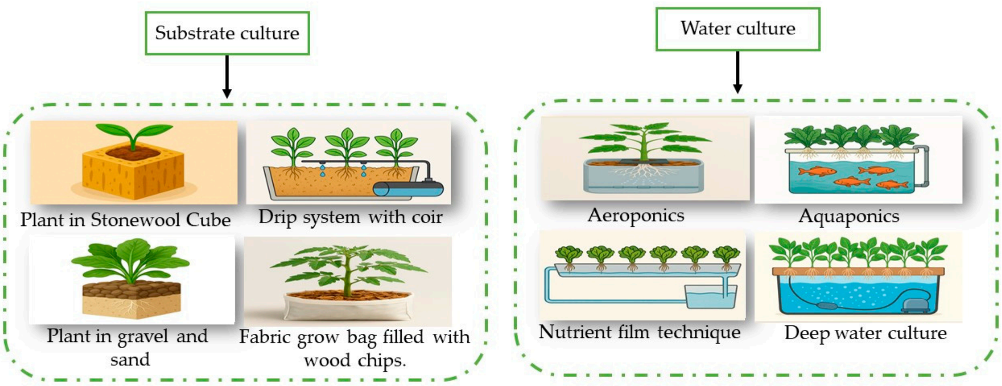


(**c**)

Figure 3. Plant growing methods (**a**), and substrate-based and water culture systems (**b**,**c**) (Illustrations created with the help of DALL·E (OpenAI, 2025)).

Previously, researchers used different substrate materials in their studies (Figure 4) and reported that the substrate can be constructed from inorganic and organic components. Organic substrates are derived from natural, biodegradable plant materials. They may undergo partial decomposition over time and often contain trace organic compounds. These substrates can influence microbial activity and may offer limited nutrient buffering capacity, although they generally do not supply sufficient nutrients for plant growth. For example, coconut coir (coco peat) is derived from coconut husk fibers and is widely used for its excellent water retention and root aeration. Peat moss (sphagnum peat) is a partially decomposed sphagnum material known for its high water-holding capacity and low pH. Sawdust is a finely milled wood by-product that is often used locally but requires careful nutrient management. Wood chips, coarse particles of softwood or hardwood, are used in blends or larger container systems. Bark, usually composted pine bark, is used in nursery production. Rice hulls or husks are lightweight and porous and are used to improve drainage. Marc, residual pulp from fruits (e.g., grape marc), is regionally used as organic amendment. Inorganic substrates are non-organic, chemically inert, and physically stable materials, often derived from natural minerals or manufactured industrially. These media do not decompose over time, are typically pH-neutral, and provide excellent drainage and aeration. Their inert nature allows for precise control of water and nutrient supply. For example, perlite, expanded volcanic glass, is lightweight and has good drainage. Vermiculite, expanded mica, retains air and water well, though less durable. Rockwool (stonewool) is made by melting and spinning basalt rock and is widely used in commercial hydroponics for seedlings and mature plants. Expanded clay pellets (LECA), baked clay beads, is reusable and excellent for ebb-and-flow or drip systems. Gravel or sand, heavy but accessible, is used in simple hydroponic setups or traditional systems like gravel beds. Synthetically produced substrates are hydrogel, foam mats or slabs (polyurethane), oasis (polyphenol foam), and so forth [76–79].

Figure 4. Some examples of the substrate materials.

Gruda [80] said that on a global scale, it is essential to note that the most commonly used materials can differ from region to region. However, peat, coir, wood, and composted materials stand out as the dominant substrate options, widely utilized worldwide for cultivating various crops. In the meantime, the mixture of different substrate materials is also used for higher growth and yield of several crops. Blok and Urrestarazu [81] estimated an area of more than 10,000 ha cultivated in rockwool slabs worldwide, including 6000 ha greenhouse area in Europe, mainly in Northern Europe. Rockwool has a low volume weight, is inert, and has a buffering capacity, limited to the quantity of nutrients and water held within the pore space of the medium [82]. The leading peat-producing countries are Finland, Ireland, Germany, Sweden, Belarus, Canada, and Russia, which account for 80% of the world's production. Commercial applications include lawn and garden soil amendments, potting soils, and turf maintenance on golf courses [83]. The extensive use of peat as a fundamental and primary component of substrates is due to relatively low costs in these areas, its excellent chemical, biological, and physical properties with low nutrient content, low pH, a unique combination of high water-holding capacity by high air space and drainage characteristics, light weight, and freedom from pests and diseases [84–86].

A review study by Barretta [87] highlighted the critical considerations in selecting suitable substrate materials for plant cultivation. First and foremost, the chosen substrate must possess a robust combination of physical, chemical, and biological properties. These characteristics are vital for creating a conducive environment that supports healthy plant root growth, particularly in challenging conditions. Additionally, the substrate must meet the specific functional requirements of the production system it will serve. The material should be meticulously designed to maintain an ideal physical structure that balances air and water. Such a balance is indispensable for promoting optimal root development and providing oxygen while retaining sufficient moisture [87–90]. Moreover, this equilibrium must be sustained throughout the entire crop production cycle, which can span several weeks to over a year, ensuring that plants thrive consistently during their growth journey. Besides, the growing medium structure is determined by the size, shape, texture, and physical arrangement of the particles it comprises [91].

Water-Based Culture

Water culture is an innovative and effective method of SLF that allows for the thriving growth of various vegetables, fruits, and medicinal plants. In a water culture system, the plant grows in a nutrient-rich water solution rather than any substrate material. The roots of the plants are hung/submerged in the nutrient solution. The upper portion, shoot, and fruit are placed above the supporting trays or growth box. Water culture is further categorized into subsystems [see Figure 5] [15–17]. Riggio et al. [92] concluded that many hydroponics systems exist. The most common types described in the literature are the nutrient film technique, deep technique film, flood and drain, continuous drip, and the wick method [see Figure 5]. Additionally, the system can be classified by container types, including window boxes, troughs, rails, buckets, bags, slabs, and beds [93]. The continuous drip technique involves a slow, steady supply of water and nutrients directly to the plant roots through a network of tubes. It minimizes water waste and ensures that plants receive consistent hydration. The flood and drain system, also known as the ebb and flow system, periodically floods the plant roots with nutrient-rich water and drains it away. This cycle promotes healthy root growth by alternating the provision of oxygen and moisture. The deep water raft culture plants are supported on a floating raft over a deep reservoir of nutrient solution. The roots dangle directly into the water, allowing easy access to oxygen and nutrients. However, the nutrient film technique involves a thin film of nutrient solution continuously flowing over the roots of the plants, which are supported on a sloped surface [94].

Aquaponics is an emerging method of local food production worldwide, using closed integrated production systems to grow vegetables and fish in various contexts. It is a form of water culture that integrates hydroponic plant cultivation with a recirculating aquaculture system [see Figure 5f]. In this setup, fish waste—primarily excreted as ammonia—is biologically transformed through nitrification into nitrite and then nitrate, which serves as a bioavailable nitrogen source for plants. This microbial conversion typically occurs in a biofilter or directly within the root zone, enabling efficient nutrient cycling [95]. The resulting nutrient-enriched water provides plants with essential macronutrients such as nitrogen, phosphorus, potassium, and various micronutrients. As plants absorb these nutrients, they contribute to water purification before it is returned to the aquaculture tanks. This process supports crop growth, reduces the need for synthetic fertilizers, and minimizes the environmental risks associated with nutrient discharge into surrounding ecosystems [96–99]. What sets aquaponics apart from other water-based systems is its dual functionality: it simultaneously produces both plant and aquatic biomass within a shared aqueous environment. As such, it offers a sustainable model for integrated food production. However, successful system operation depends on balancing fish waste production and plant nutrient uptake. One of the critical challenges lies in managing ammonia concentrations, as elevated levels are toxic to fish, while insufficient nitrates may limit plant growth [100].

Aquaponics can be implemented at various scales, from small household units to large commercial installations. Despite its growing popularity, several aquaponic system design and operation remain underexplored. These include optimizing nutrient dynamics, economic feasibility, species compatibility, and system automation. Furthermore, while integrating fish and plants offers numerous ecological and resource efficiency benefits, the co-cultivation strategy requires careful planning to ensure compatibility between species and consistency in nutrient availability [101]. Overall, aquaponics represents a promising approach to sustainable food production, particularly in urban and resource-limited settings. By converting fish-derived nutrients into plant biomass and minimizing water loss through recirculation, this system supports the cultivation of safe, nutritious food with a lower environmental footprint.

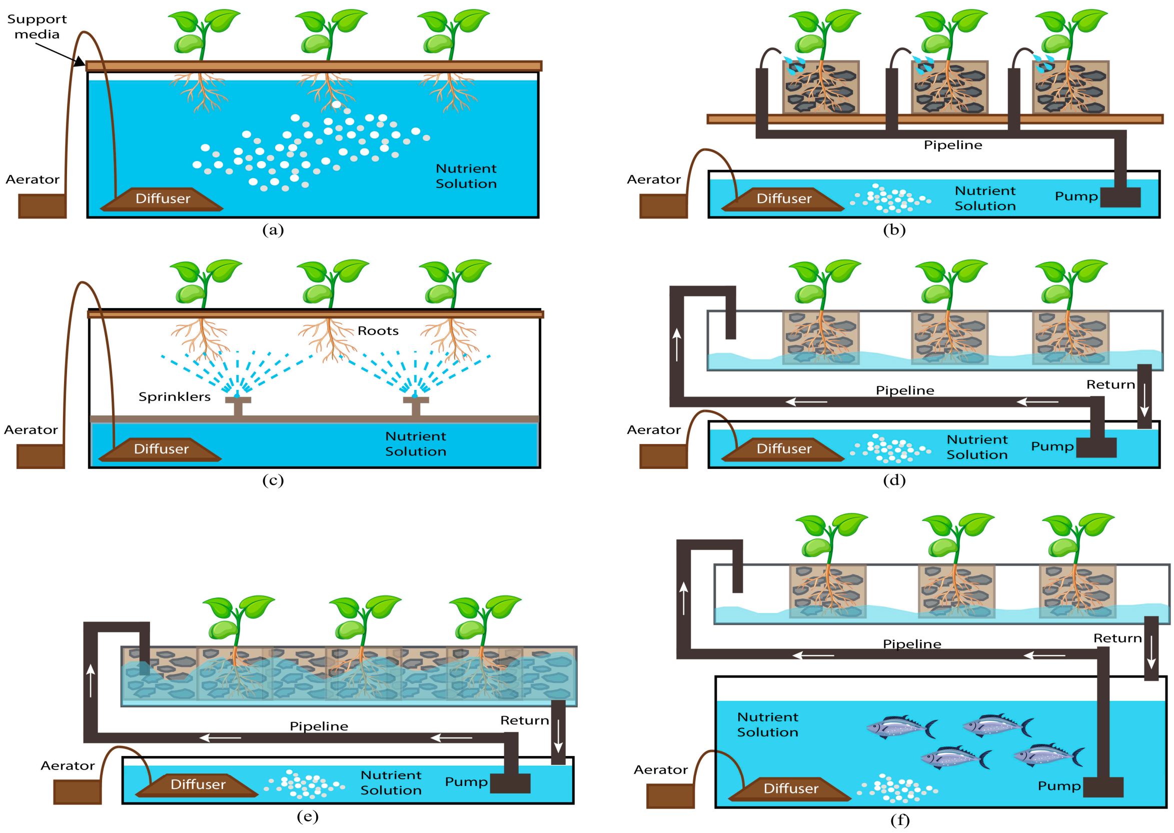


Figure 5. Different types of hydroponic systems. (**a**) Deep water culture. (**b**) Drip system. (**c**) Aeroponics. (**d**) Nutrient film technique (NFT). (**e**) Ebb and flow. (**f**) Aquaponics [102].

Aeroponics is a specialized form of water-based cultivation wherein plant roots are suspended in air and periodically misted with a nutrient solution rather than being submerged or supported by a substrate. In this system, plants are cultivated with their roots exposed inside a closed and controlled chamber, while the upper portions (leaves, stems, and fruits) extend outside [Figure 5c]. The root zone is kept in darkness to prevent algal growth and minimize physiological stress. This configuration allows for direct nutrient delivery and high oxygen availability in the root environment, supporting efficient respiration and potentially enhanced growth rates under optimal conditions [103]. Aeroponics can be broadly categorized into three types: (1) high-pressure aeroponics (HPA), (2) low-pressure aeroponics (LPA), and (3) ultrasonic fogger-based aeroponics [15–17].

High-pressure aeroponics utilizes air-assisted atomizing nozzles powered by pressurized pumps and air compressors to generate ultra-fine droplets (<50 microns). These droplets coat the root surface evenly, improving nutrient absorption and gas exchange. However, HPA systems are technically demanding: they require highly purified water, reliable electricity, and consistent maintenance to prevent nozzle clogging, root interference, and misting failure. Due to the absence of a solid medium, any interruption in mist delivery can quickly result in plant dehydration.

Low-pressure aeroponics operates at reduced mechanical and pressure thresholds, using centrifugal or impingement nozzles to deliver coarser mist droplets. While slightly less efficient in nutrient absorption, these systems are more robust and easier to manage under variable conditions.

Ultrasonic aeroponics uses piezoelectric transducers to generate nano-sized droplets in vapor form. These systems offer excellent humidity control for seedling propagation and early plant development, but are highly sensitive to mineral buildup and are usually restricted to small-scale or research settings.

Despite its technical potential, the broader application of aeroponics remains limited due to high setup costs, system fragility, and limited fault tolerance. It is most commonly used in minituber production, research facilities, or urban farming applications where space efficiency and environmental control are priorities. Unlike other soilless systems, such as substrate-based cultivation (which relies on medium porosity for oxygen diffusion) or water-based systems like nutrient film technique or deep water culture (which require active aeration through air pumps or flow dynamics), aeroponics offers passive and continuous root-zone oxygenation, which is one of its primary physiological advantages [104,105].

3.4.2. Selection of Crop-Specific Soilless Cultivation System and Nutrient Solution

SLF encompasses various advanced cultivation systems, each offering distinct benefits tailored to specific crop types. Thus, selecting the appropriate cultivation method and nutrient solution is crucial for optimizing successful crop growth, nutrient uptake, and water-use efficiency. SLF systems offer the flexibility to grow crops by providing plants with optimal nutrients, water, and environmental conditions. Due to the precise control over the growing environment, these systems can successfully cultivate crops that thrive in various settings. Leafy greens and herbs are the most commonly grown crops in SLF systems due to their short growth cycles, high turnover rates, and efficient space utilization. In addition, fruiting vegetables, root crops, and selected fruit species have demonstrated adaptability to controlled soilless environments under appropriate system management. A study by Gruda [80] reported that the question of which is the best-growing medium and the growing system does not have a single answer. This primarily depends on the location, availability, and cost of potential growing medium constituents and the envisioned crop production system. The materials for growing media must fulfil different requirements: first, they should be consistently available from batch to batch and economically feasible, i.e., the materials and production process should not be costly; and second, the growing medium's physical, chemical, and biological properties should meet the plant's biological requirements. However, no universal substrate or mixture suits all plant species in all SLF cultivation situations [106–108].

In addition, leafy greens, such as lettuce, spinach, and kale, are best cultivated using hydroponic, aeroponic, and aquaponic systems. The suitable substrate includes rock wool, coco peat, and perlite. These crops thrive in different SLF systems that provide constant access to nutrient-rich water and minimal root support [109]. This is due to their fast growth and high nutrient uptake capacity. In hydroponic systems, the life cycle of lettuce can be significantly shortened compared to open growing methods. The NFT is well suited for cultivating lettuce, allowing for more than eight annual harvests [110,111].

Fruit-bearing crops such as tomatoes and peppers are widely cultivated in SLF systems. However, their growth characteristics—including substantial plant height, heavy fruit load, and extensive root development—require appropriate structural support and system design. These crops are not typically suited for systems like NFT, but are better adapted to lightweight crops with smaller root systems. Instead, substrate-based drip irrigation systems are most commonly used for tomato and pepper cultivation because they provide precise nutrient and water delivery alongside physical anchorage [112]. Combining irrigation and containerized substrate (e.g., grow bags or slabs) helps stabilize the plant while supporting consistent moisture and nutrient retention. Commonly used substrates include peat–perlite mixtures, coconut coir, vermiculite, and perlite, all of which provide good aeration and water-holding capacity, essential for supporting healthy root systems in high-demand crops. A well-designed SLF platform must accommodate these crops' mechanical and physiological needs, ensuring structural integrity and optimal resource delivery under controlled conditions [113].

Root vegetables, such as potatoes, radishes, and carrots, are best cultivated using aeroponics or substrate-based drip irrigation hydroponic methods. However, suitable substrate materials include expanded clay pellets, perlite, or coco peat. These vegetables need substrate materials for optimal aeration and space for root expansion. Aeroponics ensures uniform nutrient delivery and promotes high-quality root development [15–17].

Herbs such as basil, mint, and cilantro thrive best in hydroponic and aeroponics systems. However, basil yield appears to be more affected by cultivar selection than by the choice of an SLF system. Therefore, SLF basil producers should select basil cultivars based on flavor and yield, while hydroponic systems should be selected based on operational preferences [114]. In addition, suitable substrate materials include rockwool and coco peat. These plants benefit from systems that allow rapid nutrient uptake and require minimal substrate. Aeroponics enhances nutrient absorption efficiency by directly misting the roots with nutrients [115].

Flowers like orchids and roses thrive best in drip hydroponics and aeroponics systems. Suitable substrate materials include expanded clay, coconut husk chips, and bark. These plants benefit from well-drained substrates that promote aeration and maintain an optimal water and nutrient availability balance. Such systems ensure consistent growth and high-quality blooms [116,117].

In SLF, the nutrient solution is a crucial factor in plant growth and productivity and serves as the primary medium for delivering essential nutrients to plants. Unlike conventional soil-based agriculture, where plants derive nutrients from the soil, SLF systems rely on a carefully formulated nutrient solution to meet the plants' nutritional needs. Developing a proper nutrient solution is time-consuming because plant species may require nutrients in various concentrations, ratios, or chemical forms for efficient absorption. Additionally, most crop nutrient solutions, whether used in water culture or solid media culture in pots, typically employ nutrients at concentrations much higher than those found in natural soil [118]. Besides, when selecting a crop-specific nutrient solution for SLF systems, various factors come into play, including the type of crop, its growth stage, and surrounding environmental conditions. For instance, herbs often have unique nutrient requirements, focusing on specific micronutrients to enhance flavor and growth. Leafy greens, like lettuce and spinach, generally require a balanced nutrient solution with a relatively higher nitrogen concentration to support continuous vegetative growth until harvest. Meanwhile, fruiting crops, like tomatoes and peppers, benefit from increased phosphorus and potassium during the flowering and fruiting stages. Growth stages also dictate nutrient concentrations. Seedlings generally thrive on diluted solutions, while established plants require more robust nutrient profiles to support their growth and development [119–121].

In general, nutrient solutions used in SLF systems contain a balanced mixture of macronutrients—such as nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S)—along with essential micronutrients, including iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), and molybdenum (Mo) [122]. The nutrient composition refers to the precise concentrations of each ion in water solution. Over the years, extensive research has led to multiple standardized formulas tailored to different crops and growth conditions [123]. Some of the standard nutrient solutions used for growing crops in SLF are shown in Table 3.

Two critical parameters—electrical conductivity (EC) and pH—must be closely monitored and adjusted during cultivation to ensure optimal nutrient uptake and plant performance. EC reflects the total ionic concentration of the nutrient solution and serves as a practical indicator of nutrient strength; values that are too low may lead to deficiencies, while excessively high EC can cause osmotic stress or nutrient antagonisms. Similarly, pH affects nutrient solubility and availability, particularly for micronutrients like iron and manganese, and is typically maintained within a crop-specific optimal range [124].

Measurement and control of EC and pH are typically performed using portable digital meters or in-line sensors, which allow for real-time monitoring. In many commercial systems, automated dosing units are integrated to maintain target setpoints by adjusting acid–base concentrations and replenishing nutrient stock solutions. Regular solution sampling and analysis—using conductivity meters, pH meters, and occasionally laboratory-based ion-specific testing—ensure that the nutrient balance remains within desired parameters throughout the crop cycle. By maintaining a well-balanced nutrient profile and tightly controlled EC and pH, growers can achieve higher nutrient use efficiency, reduce waste, and improve yield and product quality [125–130]. These factors contribute significantly to SLF systems' environmental sustainability and productivity advantages compared to conventional soil-based agriculture.

Table 3. Some of the nutrient solutions are used to grow crops in SLF. All values are in mg/L^{-1}.

Nutrient	Cooper [120]	Hewitt [125]	Steiner [126]	Hoagland and Arnon [127]
N	200–236	168	168	210
K	300	156	273	234
Ca	170–185	160	180	160
P	60	41	31	31
Mg	50	36	48	34
S	68	48	336	64
Fe	12	2.8	2–4	2.5
B	0.3	0.54	0.44	0.5
Mo	0.2	0.004	-	0.01
Mn	2.0	0.54	0.62	0.5
Cu	0.1	0.064	0.02	0.02
Zn	0.1	0.065	0.11	0.05

3.4.3. Optimal Cultivation Conditions Required for Practicing Soilless Farming and Key Factors Influencing Water-Use Efficiency and Crop Productivity

The optimal cultivation conditions for SLF are crucial for improving plant growth, health, and yield. The successful implementation of SLF systems requires careful management of both environmental and agronomic conditions to ensure optimal crop growth and productivity. The key factors influencing plant performance in SLF systems include temperature, humidity, light intensity, the composition of the nutrient solution, and its timely management. Each parameter is critical in maintaining plant health, facilitating nutrient uptake, and maximizing yields [131,132].

Temperature is a key variable for the SLF system's plant growth, photosynthesis, and metabolic processes. For example, leafy greens like lettuce, spinach, and kale thrive within a temperature range of 18–24 °C, while fruiting crops like tomatoes and cucumbers perform best at slightly higher temperatures, ranging from 20–26 °C. Therefore, maintaining temperatures according to the crop's needs helps to avoid stress conditions such as bolting in leafy crops or blossom drop in fruit-bearing plants [133–135]. Additionally, relative humidity levels directly affect plants' transpiration rates and water uptake. Maintaining a relative humidity level between 50% and 70% for most SLF systems is recommended to prevent excessive water loss, reduce the risk of fungal diseases, and enhance nutrient uptake. Higher humidity may be required for certain crops, especially in aeroponic systems where root exposure to air increases transpiration [15,17].

An adequate supply of light is essential for photosynthesis, plant growth, and development. In indoor SLF systems, supplemental lighting, such as artificial LED grow lights, is often used to provide the required light intensity (measured in photosynthetically active radiation) and regulate the photoperiod. For instance, leafy greens typically require 12–16 h of light daily for successful vegetative growth [136,137]. Additionally, it is essential to ensure proper air circulation to prevent heat buildup and reduce the risk of fungal diseases. Maintain adequate carbon dioxide levels (approximately 400–1000 ppm) to promote optimal photosynthesis and ensure a sufficient oxygen supply to the roots, particularly in hydroponics and aeroponics [138].

The nutrient solution is a critical component of SLF, acting as both the medium for nutrient delivery and a key factor in optimizing plant growth conditions. Therefore, key concentrations of selected macronutrients and micronutrients must be supplied appropriately [139]. EC levels should also be regularly monitored to maintain the desired nutrient concentration and prevent salt accumulation. The pH of the nutrient solution significantly impacts nutrient availability and root function in SLF systems. A pH of 5.5–6.5 is recommended for SLF cultivation to optimize nutrient solubility and prevent deficiencies or toxicities [140,141]. Additionally, clean or filtered water should be used when preparing the nutrient solution to avoid contaminants that can harm plant health. The ideal water temperature should typically be between 18 °C and 22 °C to promote nutrient absorption [142]. Shareef et al. [143] highlighted the need for a systematic and balanced approach to managing nutrient solutions in SLF systems. Each plant species has specific optimal ranges for these parameters that should be monitored to prevent resource waste. Key growth parameters for any SLF system are presented in Table 4, along with their optimal ranges and relevance.

One of the most essential aspects is establishing a regular maintenance schedule tailored to the system's needs [19]. This will ensure smooth, trouble-free operation, minimize costs, and support high plant production over the long term. In addition to routine maintenance, growers should regularly monitor power sources to ensure they are working smoothly and the nutrient reservoir tank is filled to the desired level. Regular inspections of the water delivery system are also necessary to detect potential issues, such as leaks in the nutrient delivery or drainage lines. By carefully managing these optimal cultivation conditions, growers can achieve high levels of productivity and sustainability, resulting in successful crop yields and ensuring consistent crop production while minimizing resource waste [144–146].

Table 4. Plant-specific optimal growth parameters in soilless systems adopted from [143].

Crop	pH	EC	Temp	Light	Photoperiod	A. Temp	RH
Asparagus	6–6.8	1.4–1.8	20–28	150–200	8/16	18–30	45–80
Lettuce	5–7	1.5–2.5	18–25	150–250	14–17	18–27	45–80
Parsley	6.0–6.5	1.8–2.2	18–25	150–200	16/8 or 14/8	18–30	45–80
Peppers	5.5–6	0.8–1.8	-	50–200	16/8	20–35	50–80
Strawberry	6.0	1.8–2.2	18–30	115–350	12–16	18–30	40–80
Rocket, eruca, or arugula (*Eruca sativa*)	5.5–6.0	1.5–1.8	18–25	150–200	16/8	18–30	45–80
Basil	5.5–6.5	1.1–1.6	18–24	80–250	16/8	18–30	50–85
Celery	5.5–6.5	1.8–3	18–25	150	16/8	18–30	50–85
Kale	6–6.5	1.2–1.8	18–25	150–250	16/8	18–30	50–80
Leek	6.5–7	1.4–1.8	18–23	150–250	(12–14)/(12–10)	18–30	60
Tomato	5.5–6.5	2–4	NM	50–200	15/9	NM	NM
Okra	5.5–6.5	2–2.4	NM	NM	NM	20–35	50–80
Rhubarb	5.5–6.0	1.6–2.0	NM	NM	NM	NM	NM
Rose	5.5–6.0	1.5–2.5	NM	NM	NM	NM	NM
Sage	5.5–6.5	1.0–1.6	NM	NM	NM	NM	NM

Note: EC (Milli Siemens cm^{-1}), Temp (temperature of nutrient solution °C), Light (lighting intensity PPFD, µmol $m^{-2}s^{-1}$), Photoperiod (hours (h) (light/dark)), A. Temp (ambient temperature, °C), RH (relative humidity, %), and NM (not mentioned).

3.4.4. Designing the SLF Systems and Steps to Initiate SLF: A Practical Guide for New Growers

Designing an effective SLF system requires careful selection of materials and addressing the specific challenges that each farming method presents. Each system type has its own set of materials and challenges, but they can be overcome with the right combination of components and careful management.

In solid media culture systems, inert substrates such as coco coir, rockwool, perlite, vermiculite, and expanded clay pellets are used. These materials support the roots, help retain moisture, and provide aeration. Thus, choosing the right substrate for different crops can be tricky, as moisture retention varies between materials. Efficient irrigation systems and well-designed plant growth chambers (buckets) are also necessary to avoid overwatering and support plants.

Water culture systems, for instance, depend on the precise delivery of nutrients through water. The key components of a water-based system include nutrient reservoirs, efficient water pumping systems, growth boxes, plant holders, and aeration systems to ensure plants receive enough oxygen. For optimal plant health, sensors that monitor the pH and electrical conductivity of the nutrient solution are essential. Furthermore, water culture systems rely heavily on electricity for water circulation and aeration, making them vulnerable to power failures. This highlights the need for backup systems and careful management, especially in aquaponics and hydroponics. Controlled environment farming integrates automation, sensors, and artificial intelligence to carefully manage temperature, humidity, CO_2 levels, and lighting. This allows for year-round crop production under ideal conditions. However, this system demands a considerable up-front investment in advanced climate control technologies, IoT monitoring systems, and backup power solutions. Maintaining these precise environmental parameters requires expert knowledge to calibrate the system and make real-time adjustments to ensure plants stay healthy and productive.

In addition, establishing an SLF system requires several critical phases [Figure 6]. SLF provides notable benefits, including water conservation, accelerated plant development, and diminished pest problems; nevertheless, it also poses hurdles such as substantial initial expenses, system intricacy, and the necessity for continuous technical oversight. Consequently, before implementing any SLF system, cultivators must comprehensively grasp the special needs of their selected crops and the principles of the chosen SLF technique. Every crop possesses distinct requirements for growth medium type, selected material characteristics, temperature, light, and nutrients in SLF systems. Also, formulating a comprehensive budget for establishment and upkeep while anticipating obstacles is essential [147–149].

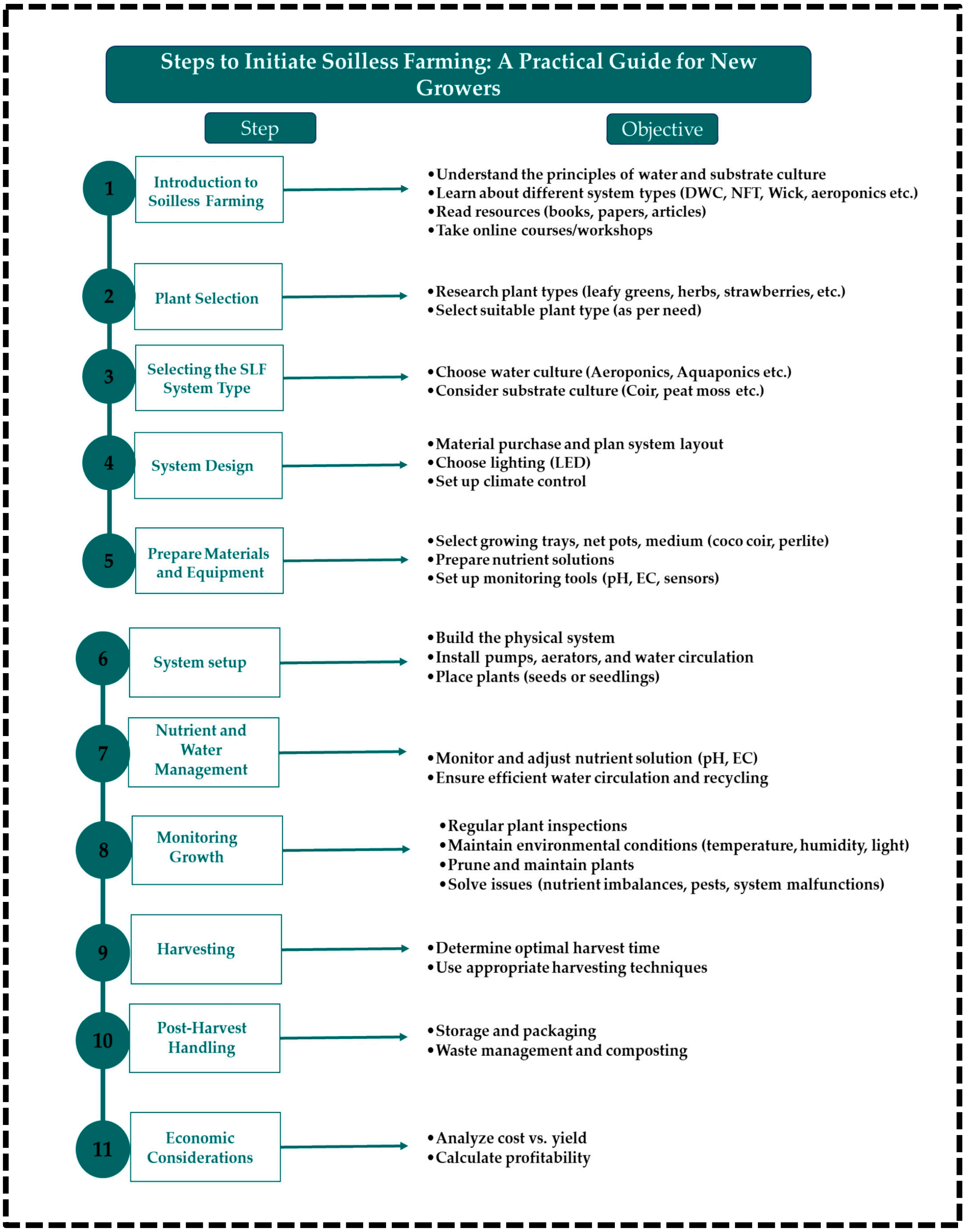


Figure 6. Steps to initiate SLF: a practical guide.

Initially, growers should acquaint themselves with various SLF methods by leveraging resources such as literature, academic articles, online instructional materials, and workshops to acquire practical expertise. Upon collecting this information, cultivators must determine whether to implement a water culture or solid media system, considering their objectives and available resources. When selecting a substrate system, it is crucial to assess materials such as coconut coir, perlite, or rockwool for their appropriateness. Conversely, if they choose a water culture, they should evaluate alternatives such as hydroponics, aeroponics, and aquaponics [150,151].

Secondly, growers must ascertain crops appropriate for the proposed SLF system, highlighting leafy greens, herbs, or fruiting plants according to market demand or personal preference or based on available space, climate, and budgetary constraints. Once the grower comprehends the crop's requirements, the chosen system necessitates fundamental components, including plant holders, cultivation beds, chemicals, nutrient reservoirs, pumps, aeration stones, LED lights, and pH, EC, and nutrient regulation instruments. Moreover, environmental regulation is a crucial part of SLF design, encompassing the management of temperature, humidity, and light, particularly in indoor or controlled cultivation settings. The selection and concentration of appropriate nutrient solutions are key to the success of SLF. Accordingly, the cultivator must develop a complete proposal for the proposed system, considering spatial dimensions, illumination, and air circulation, and should establish mechanisms for accurate temperature and humidity regulation to improve growing conditions [152–154].

Thirdly, cultivators must gather and organize the requisite supplies and equipment to implement the planned system, including grow lights, pumps, reservoirs, nutritional solutions, and so forth. Subsequently, the system is constructed by the specified design, perhaps incorporating the assembly of grow beds, reservoirs, and irrigation systems. It must be verified that all electrical components and their connections are securely placed and operating properly [155].

Fourthly, the cultivator must choose superior-quality seeds or seedlings appropriate for the proposed SLF system. In SLF, both methods of crop transplanting involve directly placing uniform-growing seedlings into the system, while crop seeds can also be directly sown into the growing media. Before crop transplanting, the plant's density must be maintained. Modifying plant density in SLF facilitates appropriate air circulation and nutrient absorption, which can directly influence plant health and yield [156,157].

Fifthly, troubleshooting is an essential factor of SLF, and growers can face any obstacles, such as nutrient imbalances, pest infestations, or water quality concerns. Therefore, the farmer must consistently monitor and modify the system according to sensor feedback or manual observations to augment performance and yields. Consequently, the SLF system requires regular maintenance, encompassing equipment cleaning, pH and EC level monitoring, and preventing blockages or nutrient accumulation. The grower must quickly address these issues to ensure a smooth system until harvest, enhancing plant growth and yield.

Sixthly, the cultivator must ascertain the ideal time for harvesting the crops, considering personal needs, crop maturity, and market demand. When crops become ready for harvest, the harvesting process must be carried out carefully to avoid damaging crops and the SLF system. After harvesting the crops, the grower must cleanse the crop roots and all other instruments, adequately package them, and store them as required [17,158,159].

Finally, the grower must conduct a comprehensive financial analysis to assess profitability when adopting any SLF system, ensuring long-term sustainability. The initial expenditure includes several essential components: infrastructure, equipment, and labor. Along with the initial setup, ongoing operational expenses must be considered to assess the system's viability. Recurring costs include electricity for lighting, water circulation, and climate control systems [160,161].

The technical principles discussed in this manuscript—system architecture, nutrient management, climate control, and operational protocols—are applicable across scales, from commercial facilities to domestic units. With informed design and maintenance, users can improve system efficiency and reliability. However, SLF performance remains context-dependent, shaped by investment capacity, infrastructure access, and user proficiency. Therefore, SLF should not be seen as a universal solution, but as a targeted, adaptable approach that contributes to food system resilience when implemented under suitable conditions.

3.4.5. Comparative Analysis of Different Soilless Farming Systems

Innovative SLF systems, such as water and substrate culture, offer unique crop yield and scalability advantages but vary in their operational requirements and potential applications [162,163]. Therefore, a comparative analysis of different SLF systems can provide insight into efficiency, productivity, and sustainability. Hydroponics involves growing plants in a nutrient-rich water solution, eliminating the need for soil. However, it has high initial setup costs and requires technical knowledge to maintain nutrient levels. Aquaponics combines hydroponics with aquaculture, where fish waste is a plant nutrient source. This creates a symbiotic environment that can sustainably produce both fish and vegetables. However, it requires plant and fish care knowledge and involves more complex system management. Aeroponics suspends plants in the air and mists their roots with a nutrient-rich solution. This method utilizes water and nutrients efficiently, promoting faster growth due to its high oxygen availability. The disadvantages include a complex system requiring monitoring and maintenance and a higher risk of plant stress if misting fails. Substrate-based systems utilize a growing medium, such as coconut coir or rockwool, instead of soil. These systems provide a stable environment for root systems and are easier to manage than other SLF systems. However, some substrates can degrade over time and require replacement, and there are limitations in nutrient delivery compared to hydroponics [164–166].

In addition, Vafaeian et al. [167] assessed the morpho-physiological, biochemical characteristics, and antioxidant capacity of lemongrass cultivated in an SLF compared to traditional soil-based cultivation at various harvesting times (two harvests). The experiment was performed under controlled conditions, with a 12-h light cycle, diurnal temperatures set at 25 °C and 18 °C, and a relative humidity range of 65–75%. The study highlighted key differences between SLF and soil-based farming. In SLF, plants showed higher chlorophyll (a and b), carotenoid content, relative water content, plant height, leaf number, and biomass (25% more in the first and 27% more in the second harvest). Overall, SLF improved morpho-physiological traits and antioxidant potential, suggesting its advantages for lemongrass cultivation and harvesting.

Roosta et al. [168] compared cucumber's growth, fruit quality, and physiological characteristics with three nutrient solutions (Hoagland, Papadopoulos, and commercial) in soil (sandy clay soil) in soil and SLF systems (cultivation bags with a mixture of cocopeat and perlite in a ratio of 50:50) in greenhouse conditions. The average minimum and maximum temperatures were 24 ± 3 °C during the day and 21 ± 3 °C at night, and the average relative humidity was 54%. Their results showed that the SLF increased plant height (13%), number of nodes (9.4%), internode distance, number of leaves, leaf area (31.45%), fresh and dry mass of shoots, fresh (21%) and dry (33%) mass of roots, number of flowers (9.4%), number of fruits (10.12%), and fruit diameter (19.5%); thus, SLF increased the yield per plant and cultivation area (52%). Overall, SLF using the Hoagland nutrient solution significantly enhanced growth and yield characteristics, as well as both the quantitative and qualitative traits of the fruit and physiological characteristics, compared to the other treatment methods.

Abu-Zahra et al. [169] cultivated lettuce in various SLF methods (deep water culture, cocopeat media, peat moss and perlite media (1:1), and mixture of soil, peat moss, and perlite media (1:1:1) to identify the most effective planting system in a greenhouse experiment. Their study found the hydroponic system positively impacted all plant growth parameters, including head fresh weight, head dry weight, leaf fresh and dry weight, root fresh and dry weight, root length, number of leaves, and leaf area. However, cocopeat culture treatment produced the highest leaf moisture content, while using soil in amendments reduced root penetration, negatively reflecting the root-to-head fresh and dry mass ratio.

Alizeah et al. [170] evaluated the effects of three different cultivation systems (nutrient film technique, aquaponic, and loamy soil) on nutrient uptake, water use efficiency, and biochemical properties of watercress during the 2022–2023 growing period. The plants were grown in a greenhouse with a natural (12:12 h light-dark cycle) at 28 °C, 45% humidity for 180 days, Hoagland's solution, and Nile tilapia fish were used. The different cultivation systems significantly impacted lemongrass yield, daily water use, and water-use efficiency. In hydroponics and aquaponics systems, lemongrass yield increased by 92.3% and 40%, respectively, compared to the soil system. Conversely, daily water usage was approximately 2 and 1.3 times lower in hydroponics and aquaponics systems, respectively, compared to the soil medium. This reduction may stem from less competition for moisture between soil and weeds in soilless systems. Additionally, these systems often have shorter growing cycles that require less water and lower evapotranspiration rates. Overall, soilless systems resulted in faster plant growth and higher yields. This efficiency can lead to reduced inputs and less environmental impact than traditional farming.

Chamoli et al. [171] studied the hydroponically (NFT system) and soil-grown (2:1 mixture of soil and farmyard manure) lettuce by choosing Hoagland's solution. All the measured parameters were significantly higher in hydroponics than in lettuce plants cultivated in a soil system.

Another study by Erdal and Aktaş [172] examined the effects of different growth media (cocopeat, perlit, leonardite, vermicompost, and peat) on tomato nutrition, growth, and yield as an alternative to cocopeat. A total of 17 combinations were tried by keeping the peat constant and mixing 1:1, 1:2, and 1:4 (v/v) ratios. The mixtures were filled in 7 L pots with water using drip irrigation. Their study found that the highest fruit yields were obtained from plants grown solely in peat and 1:1 peat + vermicompost medium. As a result, it was seen that most peat-containing growth media, especially peat + vermicompost mixtures, can be used in soilless tomato cultivation as an alternative to cocopeat.

Hazrati et al. [173] determined the effects of macronutrient concentrations (two levels of N and two ratios of P and K) during three harvest times on the growth, quality, yield, and shelf life of three mint species in SLF practiced in an automatically controlled greenhouse. The plants were subsequently transferred into pots utilizing the Neuhaus Humin substrate, a peat-based horticultural medium. Max, min, and mean temperatures during the growing period in the greenhouse were 43 °C, 2 °C, and 17.3 °C, the temperature of the greenhouse was 20–25 °C, and the dissolved oxygen was between ca. 7 and 9 ppm throughout the growing period. Their study reported that the increase in nitrogen concentration in the nutrient solution hurt specific quality parameters, such as higher $NO3-$ content. Therefore, combining optimal nutrient solution ion concentration and appropriate species is essential to obtain suitable yield and quality and ensure the mint plants' shelf life in the SLF system.

Sadek et al. [174] quoted that according to Lakhiar et al. [16], applying sophisticated monitoring technology tools in SLF systems may allow for remote monitoring and managing all system parameters. As a result, it may reduce system casualties caused by the time-consuming manual tracking and regulating process. Thus, their study designed an intelligent nutrient film technique and aeroponic system based on the Internet of Things in the greenhouse. The greenhouse was connected to various tools for automatically controlling the weather conditions inside the greenhouse, consistent with the plant type and season. It was equipped with IoT sensors to automate and store system parameters and provide a graphical interface for remote access. Their study reported that the developed IoT-based system enables real-time monitoring and control of critical factors influencing SLF. This allows for early detection and automated response to system fluctuations, helping to prevent issues before they impact crop performance. Additionally, the system facilitates precise assessment of environmental and technical conditions, enhancing water and energy efficiency, reducing labor input and operational costs, and minimizing the need for fertilizers and pesticides. Compared to conventional agriculture, the developed NFT and aeroponic systems using IoT saved 80–90% of water and fertilizer, doubled productivity per area, and reduced the time to yield to 45 days, compared to 75 days in traditional agriculture. Broćić et al. [175] assessed the application of aeroponics and the conventional production system (substrate of sand and perlite (1:1)) of virus-free potato minitubers of three varieties of potatoes (Cleopatra, Kennebec, and Agria). They reported that in the aeroponics system, with all three varieties (Kenebec (6.46), Agria (5.71), and Cleopatra (4.01) minitubers), an average of 17.87 minitubers was obtained, which was 5.39 times more than in the conventional substrate culture. Another study by Tican et al. [176] evaluated four potato varieties by applying two cultivation methods: aeroponic and substrate (with a peat–perlite mixture). Their results showed that aeroponic culture was superior in miniaturization (average 12 minitubers) compared to substrate culture (average 6.94 minitubers). Both studies stated that minituber production is typically higher in aeroponic systems than in substrate-based culture due to the increased oxygen availability to developing stolons and tubers, which enhances root respiration and metabolic activity. The absence of a solid medium reduces physical resistance, allowing for more uniform tuber initiation and expansion.

Weingarten et al. [177] encompassed various (1) soilless propagation methods including aeroponics, horticultural (phenolic) foam, and rockwool; (2) transplant timings; (3) aeroponic spray intervals; and (4) aeroponic reservoir nutrient concentrations to elucidate their impact on rooting and growth parameters amongst two Cannabis cultivars. The study reported that aeroponics was as effective as, and in some cases more effective than, soilless propagation media for root development and plant growth. In aeroponic systems, continuous spray intervals, compared to intermittent ones, result in a better promotion of root initiation and plant growth. Finally, the findings suggested that aeroponic propagation, compared to alternative soilless methods, is a rapid and efficient process for cultivating vegetative cuttings of Cannabis and offers sustainable advantages in resource conservation and preservation.

El-Helaly and Darwish [178] evaluated the growth, yield, and chemical compositions of Frire red lettuce cultivated with the nutrient film technique, aeroponic, and sandy substrates at a controlled experimental fiberglass greenhouse. Their study found that the hydroponic system resulted in the highest number of leaves, while the aeroponic system produced the tallest plants and the longest roots. The hydroponic system also led to the highest shoot fresh weight and yield, surpassing sandy substrate yields by 2.51 times and aeroponic by 2.30 times. The nutrient film technique also exhibited the highest nitrogen, phosphorus, and potassium percentages. At the same time, the sandy substrate had the lowest nutrient content but recorded the highest dry matter in the plant after six weeks.

Carroll et al. [179] compared the growth of lettuce crops grown using soil (experimental field plot) and SLF (deep water culture) methods. Their study found that the lettuce crops grown using SLF increased in wet weight statistically and significantly faster than those grown in soil ($p < 0.0001$).

Wimmerova et al. [180] used life cycle assessment to compare deep water culture and aeroponic cultivation with soil cultivation (the Forestina standard propagation substrate). Their focus was on biomass production and bioactive compounds like caffeine and theobromine. The results showed that the coffee arabica had higher bioactive content and biomass in aeroponics. At the same time, Senecio bicolor grew better in deep water culture but had no significant increase in bioactive substances. Life cycle assessment results revealed that fertilizer, diesel, water, and electricity consumption had substantial environmental impacts, particularly in ecotoxicity, human toxicity, and global warming. Thus, sustainable practices in SLF need to address these issues.

Bafort et al. [181] assessed hemp flower cultivation's economic viability and quality for two varieties, Santhica 27 and Félina 32, in SLF (nutrient film technique) practiced in the greenhouse and open-field systems. It found that greenhouse cultivation yielded higher cannabinoid production but significantly higher operating costs (13–15 times more than open-field production), and various factors can account for those differences. These factors include significantly lower crop density (approximately 30 times lower in the greenhouse), the absence of adverse weather conditions and wind stress, consistent shading against excessive sunlight exposure, and the application of continuous mineral nutrition and water supply through a hydroponic solution set the greenhouse apart from the field. In addition, the economic analysis suggests optimizing greenhouse techniques and reducing labor costs could improve the feasibility of hemp flower production.

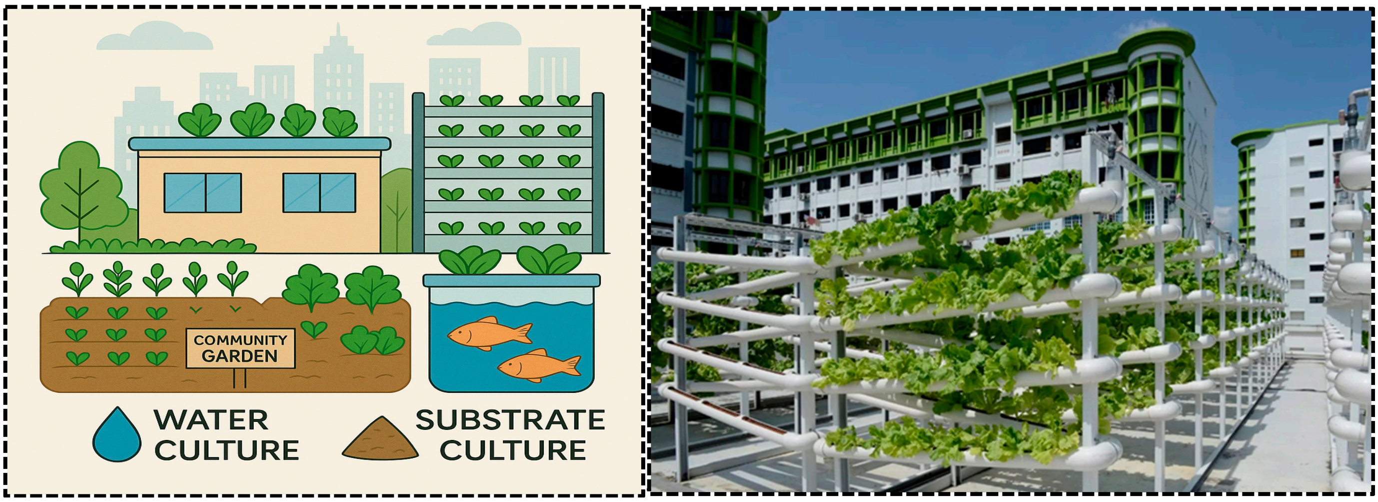
Pasch et al. [182] cultivated basil in three hydroponic subsystems within a decoupled aquaponic system in a greenhouse: (i) a modified commercial aeroponics system (AERO), (ii) a dynamic root floating (DRF) system, and (iii) a floating raft system. Process water from intensive African catfish rearing was used as the sole nutrient source, without adding fertilizers. Plants were illuminated at 14.50 klx with a photosynthetic photon flux density of 270 $\mu mol/m^2 \cdot s$. The study found that African catfish exhibited efficient growth, with low feed conversion ratios (as low as 0.84) and high specific growth rates, especially in smaller individuals. Although the water quality generally supported plant development, initial deficiencies in potassium and iron, associated with elevated pH, led to visible basil stress. As pH levels declined and EC increased, plant health improved. The AERO significantly outperformed the DRF and raft systems in plant growth parameters, including total biomass and leaf yield. AERO plants developed shorter but denser roots, which enhanced nutrient uptake and shoot growth. DRF and raft systems showed comparable performance, while higher SPAD values in AERO and DRF suggested better nitrogen status than in the raft system. The findings indicate that aeroponics holds strong potential for future food production due to its high productivity and efficient resource use. However, supplementation with potassium and iron is essential for large-scale application.

Barbosa et al. [59] determined whether hydroponic lettuce production is a suitable and more sustainable alternative to conventional lettuce production in Arizona. Data related to the traditional method was obtained from crop budgets and governmental agricultural statistics. In contrast, data regarding the hydroponic production of lettuce was developed using engineering equations and values reported in literature, which were then applied to a hypothetical 815 square meter-enclosed hydroponic greenhouse located in Yuma, Arizona. This greenhouse was assumed to use the nutrient film technique of growing hydroponic lettuce, with temperature controls, supplemental artificial lighting, and water circulation pumps. The study found that lettuce yields from hydroponic farms were 11 times higher than those from traditional methods. However, this came at the cost of higher energy consumption. According to the same study, lettuce yields per greenhouse unit can require up to 90,000 to

11,000 kJ/kg/y, while traditional methods only need 1100 to 75 kJ/kg/y. This translates to 82 times more energy consumption of hydroponic farms than traditional ones.

3.5. Application of SLF in Sustainable Urban Horticulture

Urban agriculture/horticulture (UA) has become a strategic response to modern challenges such as food insecurity, urban population growth, and the environmental costs of conventional farming. Although often seen as a modern innovation, UA has historical roots—from wartime "victory gardens" in the United States to Edo-era Japanese cities, where food production was integrated into urban life [183–185]. As nearly 68% of the world's population is projected to migrate to urban areas by the year 2050, UA offers the potential to help these vulnerable, populated cities grapple with the subsequent challenge of food insecurity [186]. Today, the role of UA has evolved, aligning with sustainability goals and offering solutions to contemporary urban pressures. In broad terms, UA encompasses food cultivation, processing, and distribution within urban and peri-urban areas. Practices include rooftop gardens, community plots, hydroponic and substrate systems, and, increasingly, vertical farms. These systems offer alternatives to conventional agriculture by reducing dependency on arable land, lowering transport-related emissions, and enabling localized, year-round food production [186,187]. With industrial-scale production, rural agriculture focuses on monocultures, which sacrifice the diversity of the cultivated crops and accelerate soil degradation. Conversely, UA can provide a sufficient variety of crops and vegetables for a person's daily consumption while occupying only 10% of urban space [188]. Vertical farming, a prominent form of UA, involves growing crops in vertically stacked layers within controlled indoor environments. These systems are typically located in buildings, warehouses, or retrofitted urban spaces and rely heavily on SLF techniques such as hydroponics or substrate culture, which deliver nutrients directly to plant roots without soil [see Figure 7]. This approach maximizes land-use efficiency and enables high-density food production in cities where space is limited. It also conserves water, avoids soil degradation, and reduces pesticide use due to the controlled environment [189,190].



(**a**) (**b**)

Figure 7. Schematic view of UA setup (**a**) and UA setup in Singapore (**b**), adapted from https://www.loriene.com/vertical-farming-singapore (accessed on 1 May 2025).

UA also supports circular resource use. Many systems recycle water through closed-loop irrigation and incorporate rainwater harvesting or greywater reuse. Aquaponic setups, for example, pair fish farming with hydroponics to create nutrient cycles where fish waste fertilizes plants. These self-sustaining models are particularly valuable in water-stressed environments [188,191]. Beyond food production, UA contributes to broader urban resilience. Locally grown food shortens supply chains, improves access to fresh produce, and reduces vulnerability during crises, such as during the COVID-19 pandemic, when global logistics were disrupted and food prices surged [192]. Community farms can also provide social benefits, offering education, employment, and a platform for civic engagement [193].

Nevertheless, several challenges persist. Limited access to urban land, inconsistent regulatory frameworks, and the high upfront costs of advanced systems continue to hinder widespread adoption, particularly in lower-income communities [194,195]. Some urban greening efforts have even unintentionally fueled gentrification, pushing out the very communities they were meant to benefit. Moreover, small-scale farms often struggle with economic viability due to limited equipment access and labor-intensive methods. In contrast, large-scale commercial farms may lack regulatory oversight or remain in early developmental stages [196,197]. Despite these limitations, urban agriculture offers a practical and scalable path toward sustainable food systems, primarily supported by vertical and SLF technologies.

A study by Yuan et al. [188] further informed that in measuring the economic viability of UA, its economic impacts and profitability are distinguished in three levels: (a) household level, (b) city level, and (c) macro level. At the household level, the urban households directly incur economic benefits and costs involved in agricultural production, such as self-employment, exchange of products, income from sales, savings on food, and health expenditures. At the city level, there are: (a) direct benefits and costs that the farmers do not carry and (b) indirect benefits and costs in the form of positive and negative externalities. These externalities include UA's social, health, and environmental impacts in the urban setting. However, comparing different city situations remains a challenge, as these impacts depend on the policies and legislation existing in the city. At the macro level, the effects of UA are felt through its contribution to the nation's gross domestic product and the efficiency of the national food system. Moreover, UA products can supplement rural agriculture's limited supply, substitute for food imports, and boost export production of agricultural commodities [198–200].

While SLF presents promising applications for UA by addressing land scarcity, localized food access, and sustainability goals, its implementation remains subject to several constraints. Urban systems—such as rooftop hydroponics, container farms, and vertical setups—often encounter logistical and regulatory challenges, including zoning limitations, building infrastructure constraints, and inconsistent access to water and energy. Economic barriers also pose a significant limitation, as the high capital and operational costs can restrict adoption in lower-income areas, ironically, where food insecurity is often most acute. In addition, the successful deployment of urban SLF depends on local technical expertise, infrastructure, market access, and community participation, which can vary widely between urban contexts.

Although SLF has the potential to contribute meaningfully to sustainable urban food production, it should be integrated as one component within a diversified urban food system strategy, rather than as a stand-alone or universal solution.

3.6. What Are the Current Research, Challenges, Future Opportunities, and Status of Soilless Farming in China and Worldwide?

3.6.1. Global Impact of COVID-19 on Agriculture: Role of Soilless Farming

The rise and spread of the coronavirus pandemic (COVID-19) created an imbalance in all sectors worldwide, massively disrupting the global economy. Social distancing, quarantine regulations, and strict travel restrictions significantly reduced the workforce and job losses across all industrial sectors. One of the sectors most severely affected was agriculture [201]. An online published report [202] showed that, due to COVID-19, the demand for food supply increased drastically. For instance, the "food away from home" sector accounts for 10% of fruit, 32% of vegetables, 25% of dairy, and 31% of cereal. This sector accounted for at least 25–30% of the total sales of fresh fruit and vegetables. In addition to logistical challenges, households' consumption patterns at home differed from those away from home. Salisu et al. [203] stated that the declaration of a nationwide lockdown exacerbated the situation, resulting in a shortage of labor supply, a lack of availability of fertilizers, an imbalance in supply and demand, and problems associated with post-harvesting due to social distancing. Pandemic-related issues increased local food production, including early supermarket shortages, concerns about the pandemic's potential impact on commercial food systems, and a shift in free time from working from home and furloughs [204,205]. The COVID-19 pandemic exacerbated unprecedented disruptions to global food systems, exposing the weaknesses of traditional agricultural supply chains. Some literature has long acknowledged the importance of urban and rural agriculture to human health and well-being. Urban agriculture has undoubtedly proven beneficial to mental health during the COVID-19 epidemic, alleviating social isolation and enhancing mood and community [206].

Several studies [207–210] have highlighted that during the COVID-19 pandemic, SLF systems gained renewed attention in urban areas where food transportation and distribution networks were severely disrupted. These controlled-environment systems enabled localized food production independent of soil, helping to mitigate the effects of labor shortages and logistical challenges. In contexts where movement restrictions limited access to fresh produce, some households and small businesses adopted SLF to maintain a degree of food availability. Beyond its role during the crisis, SLF contributed to broader food security, sustainability, and agricultural resilience goals. Governments and private-sector actors in multiple countries have since acknowledged the potential of SLF to buffer future disruptions, leading to increased interest in controlled-environment agriculture. These systems can reduce reliance on extended supply chains and offer improved water-use efficiency compared to conventional farming methods. The pandemic catalyzed the re-evaluation of food system vulnerabilities and accelerated the adoption of innovative, resource-efficient, and climate-resilient technologies. Although not a universal solution, SLF has demonstrated adaptability under crisis conditions, supporting its role as a complementary component of resilient agricultural strategies in urban and resource-limited contexts.

3.6.2. What Is the Current Status of Soilless Farming in China and Globally?

SLF is a technologically advanced cultivation method with a developmental history that spans nearly 180 years. Initially confined to experimental studies, SLF has progressively evolved into a practical and commercially viable approach to food production. Substrate-based cultivation has seen substantial refinement among its core systems, while overall production practices continue to improve. These advancements have facilitated the gradual expansion of SLF into various industrial applications across multiple regions [211].

SLF has garnered increasing attention in China and globally as a complementary strategy to address critical agricultural and societal challenges, including food security, climate adaptation, land scarcity in urban areas, and efficient resource utilization. Although it is not designed to replace conventional soil-based farming, sustained innovation and growing interest in sustainable production systems have expanded the applicability of SLF in diverse settings. Vertical farming and controlled environment agriculture are integral to future food strategies, particularly in urban centers with limited arable land and high population densities [212]. China, in particular, is rapidly urbanizing, with the national urbanization rate reaching 65% by the end of 2021 [213]. This accelerated transformation brings opportunities and challenges, including urban food insecurity, ecological degradation, and lifestyle-related pressures such as time constraints and occupational stress. As a result, SLF is positioned to play a strategic role in China's urban food systems. In major cities like Beijing, Shanghai, and so forth, SLF offers the potential for year-round local production of fresh vegetables, reducing post-harvest losses, transportation costs, and greenhouse gas emissions.

According to Research and Markets [214], the Chinese indoor farming market is projected to reach USD 7.5 billion by 2028. This robust growth is driven by the convergence of advanced technologies, targeted policy support, and the urgent need to improve food self-sufficiency. Projects like Shenzhen's Jian Mu Tower—a high-rise building with a fully integrated vertical hydroponic farm capable of producing up to 270,000 kg of food annually—underscore the country's commitment to integrating SLF into urban infrastructure. Government-led initiatives reinforce this trajectory by promoting smart agriculture through subsidies, research investment, and technology transfer, especially in water-scarce regions such as western China.

Wang et al. [215] highlighted the energy-intensive nature of modern greenhouse operations. To address this, integrating renewable energy, particularly solar photovoltaics, has gained momentum. Photovoltaic greenhouse systems in China are demonstrating strong potential, with reported payback periods of less than nine years. These systems reduce operational energy costs and align with national sustainability goals. However, challenges such as high up-front investment and technological complexity still constrain large-scale deployment [216]. Beyond renewable energy, incorporating advanced technologies further transforms SLF practices in China. AI-integrated sensor networks, in particular, can dynamically adjust microclimatic variables to optimize yields and reduce input waste, thereby supporting China's broader goal of increasing domestic agricultural self-reliance [217,218]. Despite these advancements, Qi et al. [219] noted that greenhouse agriculture in China still faces several unresolved challenges. Further research and development are needed to improve SLF systems' sustainability, efficiency, and market responsiveness. This includes adapting crop varieties to changing consumer preferences and ensuring environmental safeguards in system design and operation.

At the global level, SLF systems are gaining traction as viable alternatives to traditional agriculture in response to climate volatility, soil degradation, and rising population pressures [220–223]. Urban centers worldwide are increasingly adopting rooftop hydroponics and vertical farming solutions, which offer significant advantages in water conservation, land-use efficiency, and reduced carbon footprints through localized production and closed-loop nutrient management [224].

In regions vulnerable to climate extremes, such as sub-Saharan Africa, the Middle East, and parts of Asia, SLF systems offer resilience by enabling food production in controlled environments. These systems buffer crops against droughts, floods, and other weather-related disruptions, making them critical tools for advancing food security and climate adaptation. Additionally, SLF supports several UN Sustainable Development Goals by improving productivity, reducing resource waste, and enabling sustainable intensification of agriculture [225].

Although a niche contributor to global food output, the SLF sector is poised for significant growth. Zhou et al. [220] project compound annual growth rates (CAGR) of 12.4% for hydroponics (2024–2030), 9.6% for aquaponics (2024–2029), and 14% for vertical farming (2022–2028), indicating strong commercial momentum.

Key market players such as HydroGarden, AeroFarms, NutraGreen, BrightFarms, Agrilution, Urban Crop Solutions, Gotham Greens, and Plenty are actively shaping the future of SLF through innovations in automation, lighting, and system integration [226]. Regionally, North America and Europe lead in adoption, driven by urban farming trends and consumer demand for sustainable, local produce. For instance, over 50% of vegetable production in the Netherlands utilizes hydroponic systems. The Asia-Pacific region, particularly China, India, and Singapore, is experiencing rapid uptake facilitated by urbanization and supportive policy environments. SLF is also gaining ground in the water-scarce areas of South America and the Middle East, while Africa is exploring its potential within broader strategies for food security and climate resilience [227–229]. In Europe, countries like Spain, Italy, France, and Greece are major producers of greenhouse vegetables. Notably, Spain's Plain of Almería hosts approximately 32,000 hectares of greenhouse cultivation, of which around 3000 hectares are dedicated to soilless systems—one of the region's highest concentrations of SLF deployment [230].

Looking forward, the evolution of SLF will be shaped by integrating digital and clean technologies. Blockchain is expected to improve traceability and food safety, while robotics and AI will enhance automation and precision. Renewable energy, particularly solar power, will remain pivotal in reducing the environmental impact of indoor agriculture. However, the need for active cooling, especially in hot climates where LED lighting generates heat, poses an ongoing challenge. Despite improved LED efficiency, excess heat accumulation increases energy demand, complicating energy balancing and limiting sustainability gains [231].

SLF's applicability extends beyond Earth as well. Ongoing research by NASA and other space agencies explores hydroponic and aeroponic methods to support food production on long-duration space missions. Similarly, SLF systems are being tested in extreme environments such as deserts and polar regions, highlighting their adaptability for global food security [15–17].

In summary, SLF presents substantial opportunities to enhance food system sustainability, especially in urban and resource-limited environments. Rapid urbanization, government incentives, and technological progress catalyze SLF's growth in China. Globally, the pursuit of climate-resilient, digitally enabled agriculture is fueling interest in SLF systems. Nevertheless, challenges such as high capital costs, energy intensity, and limited applicability to staple crops constrain broader adoption. Therefore, SLF should not be viewed as a universal substitute for conventional farming but rather as a strategic supplement, most effective when adapted to the specific ecological, economic, and spatial contexts in which it is deployed.

3.6.3. Future Prospects, Current Challenges, and the State of Research and Innovation in Soilless Farming

SLF holds substantial promise in addressing global food security, improving crop productivity, and reducing agriculture's environmental footprint. With advancements in automation, precision agriculture, and sustainable resource management, SLF is increasingly positioned as a key pillar in urban farming, climate-resilient food systems, and controlled-environment agriculture, including space-based food production [232–234].

Current research efforts are focused on optimizing system designs, enhancing input efficiency, and extending crop diversity beyond leafy greens. Vertical farming, a subset of SLF, is being developed to support high-density, year-round cultivation in urban settings [17]. Precision irrigation technologies with real-time sensors and data analytics enable dynamic water and nutrient-level adjustments, improving resource-use efficiency and plant health. Simultaneously, studies are refining nutrient formulations tailored to specific crop needs, maximizing yield and quality while minimizing excess fertilizer application through recirculation systems [235–237].

Despite these advances, scaling SLF beyond leafy vegetables and herbs remains technically challenging. High-value fruiting crops—such as tomatoes, cucumbers, and strawberries—can thrive under optimized greenhouse conditions. Still, high operational costs, system complexity, and the need for specialized management constrain broader adoption. Research is focused on enhancing nutrient delivery systems, refining environmental control strategies, and developing cultivars better suited to soilless environments [238,239].

Microbial balance within SLF systems, especially in hydroponics, has also become a critical area of focus. Unlike soil-based systems that benefit from natural microbiota, SLF environments are vulnerable to microbial contamination, including harmful bacteria, fungi, and algae. Saldinger et al. [240] emphasized the importance of maintaining strict hygiene, as poor sanitation or contaminated inputs can lead to food safety risks—even though pathogens like *E. coli* do not penetrate plant tissues, they may persist on surfaces. Advanced decontamination protocols, high-quality planting materials, and stringent phytosanitary measures are essential to ensure system integrity.

Energy management and climate control also pose technical challenges. Ongoing research into LED lighting systems is optimizing spectral quality, intensity, and photoperiods to enhance photosynthesis while reducing energy consumption. CO_2 enrichment strategies, although effective in fully enclosed or cold-climate systems, remain less feasible in naturally ventilated greenhouses, where maintaining optimal CO_2 levels (600–1000 ppm) is complex [241–243]. Renewable energy integration—particularly solar and wind power—aims to reduce reliance on conventional electricity grids, though cost and storage constraints limit current adoption.

Sustainability continues to guide innovation in SLF. Closed-loop systems, such as aquaponics, promote resource circularity by using fish waste as plant nutrients and repurposing crop residues. Life cycle assessments evaluate SLF's carbon footprint, highlighting the benefits of localized production, minimized waste, and reduced transportation emissions [244–246].

Substrate science is another area of intense study. Fields et al. [247] noted that ideal SLF substrates must retain moisture, provide aeration, support stable temperatures, and be chemically and biologically inert. Regionally available and economically viable substrates—such as biochar—are being tested for their ability to maintain system stability and minimize agrochemical loss [248–251].

Economic feasibility is increasingly emphasized in SLF research. Studies aim to develop scalable and cost-effective systems with reduced initial investment, low maintenance, and long-term viability. Researchers are also exploring how SLF can be integrated into existing supply chains and urban food networks to improve accessibility and profitability [252–254].

Microbiome research in hydroponics is emerging as a critical domain. Thomas et al. [255] stressed that beneficial and pathogenic bacteria often belong to the same genus, necessitating strain-level identification and control. While in vitro studies are common, large-scale in vivo trials remain limited. Research must shift toward understanding pathogen ecology, resistance mechanisms, and biocontrol efficacy in real-world conditions. Regulatory hurdles also limit the commercial deployment of microbial consortia, despite their potential in disease suppression and yield improvement.

Renganathan et al. [256] highlighted the integration of microalgae and cyanobacteria in SLF systems as a promising pathway to improve nutrient cycling and stress tolerance. These microorganisms enhance bioavailability and maintain microbial balance in the root zone. However, their commercial application hinges on cost-effective and energy-efficient biomass production. Research is exploring the co-cultivation of microalgae in closed-loop systems to reduce wastewater, improve nutrient recovery, and boost overall system efficiency.

3.6.4. Soilless Farming in Developing Regions: Challenges and Opportunities

While SLF systems offer notable advantages for sustainable agriculture, their deployment in developing regions remains constrained by a complex interplay of economic, technical, infrastructural, and policy-related challenges [257]. One of the foremost barriers is the high capital investment required to establish and operate SLF systems. Vertical and hydroponic farms require irrigation, lighting, nutrient circulation, and climate control infrastructure. These requirements elevate capital and operating costs, especially in environments with high energy expenses or limited grid access [17,258].

Urban land scarcity and high property costs further complicate adoption. Although proximity to consumers reduces logistical costs and spoilage, the high value of urban real estate often competes with agricultural uses. Teoh et al. [145] noted that adaptive reuse of underutilized spaces, such as rooftops and abandoned buildings, offers a partial solution, but its feasibility is contingent upon favorable land-use policies and regulatory frameworks [259].

The technological and knowledge gap among farmers in many low- and middle-income countries is a persistent challenge. SLF demands precise management of nutrient regimes, environmental parameters, and pest control. However, access to technical expertise, training programs, and extension services remains limited. Savvas and Gruda [113] and Bahri et al. [260] emphasized the dominance of traditional practices and the lack of capacity-building mechanisms tailored to SLF technologies. Additionally, weak infrastructure—including unreliable electricity, poor internet connectivity, and inadequate supply chains for inputs—further impedes implementation [261,262].

Market integration poses another significant hurdle. High-value crops commonly grown in SLF systems, such as herbs and leafy greens, often lack stable market outlets in developing regions. Price volatility, weak aggregation networks, and limited cold-chain logistics reduce profitability and discourage adoption by smallholder producers [262–264].

Despite these constraints, localized innovations and targeted interventions are revealing new pathways. Fei et al. [265] suggested that modular, low-tech SLF designs adapted to local conditions can reduce costs and improve feasibility. Strategies such as integrating SLF units with waste heat recovery, using passive ventilation, and constructing systems with recycled or locally sourced materials are also being explored. Financial tools—including subsidies, tax incentives, and microloans—can help democratize access to SLF technologies, especially when bundled with community-based farming models.

Nevertheless, a balanced perspective is essential. SLF is not a one-size-fits-all solution, and its effectiveness depends on socioeconomic context, environmental conditions, and institutional support. A strategic approach—grounded in affordability, knowledge transfer, infrastructure development, and community engagement—is critical to unlocking the potential of SLF in developing regions. When thoughtfully implemented, SLF can complement conventional agriculture by increasing food production resilience, especially in urban and peri-urban zones where resource constraints are most acute.

3.7. How Do Artificial Intelligence (AI), Internet of Things (IoT), and Smart Horticulture Tools Enhance the Efficiency, Productivity, and Sustainability of Soilless Farming?

In the context of global warming and its adverse effects on agricultural productivity, adopting advanced technologies, particularly the IoT and AI, is increasingly recognized as an essential tool for improving traditional agriculture's efficiency, precision, and sustainability [266]. These tools enable farmers to monitor and manage ongoing farm activities remotely, enabling real-time data collection and analysis for large-scale agricultural operations [267]. Traditional irrigation methods are being progressively changed by introducing precision irrigation techniques, such as drip and micro-sprinkler systems, which are optimized through IoT-based smart sensors to mitigate water scarcity and improve water-use efficiency. Modern smart sensors and automatic robotics tools are successfully deployed to perform several tasks without human involvement [268–270]. These tools are vital in automating time-consuming tasks such as irrigation, pest control, and weed removal. These tools are integrated with IoT-based technologies via wireless sensor networks [271]. For instance, remote sensing, sensor cameras, and unmanned aerial vehicles with advanced imaging capabilities for site-specific monitoring, nutrient management, and aerial spraying [272–276]. In the meantime, AI and machine learning algorithms have been used extensively in agricultural applications, including seed classification, soil moisture estimation, weed and pest detection, nutrient analysis, fruit and vegetable grading, and crop yield prediction. ML algorithms and advanced techniques, such as support vector machines, deep learning, artificial neural networks, convolutional neural networks, Naïve Bayes, and tree-based models, have demonstrated high accuracy in solving complex agricultural problems. Several studies have stated that these AI-driven approaches enable farmers to improve farm input use, decrease the overuse of water, pesticides, and fertilizers, mitigate crop diseases, and enhance productivity and profitability [16].

In addition, the recent technological advancements in horticulture have significantly transformed traditional SLF systems, making them automatic, more efficient, sustainable, and user-friendly. Integrating AI, IoT, and innovative horticulture tools in SLF involves the seamless combination of smart sensors, automation, and AI-driven analytics. This facilitates data-driven decision-making and plays a transformative role in enhancing SLF operations. The IoT facilitates real-time monitoring and automation through various connected devices and sensors; environmental sensors meticulously track temperature, humidity, CO_2, and light intensity. Nutrient and water quality sensors monitor pH levels, EC, dissolved oxygen, and nutrient concentrations. Root zone sensors assess moisture, oxygen levels, and nutrient uptake. Automated systems, including smart pumps and valves, regulate the flow of water and nutrients, while climate control systems maintain optimal temperature, humidity, and lighting conditions. Furthermore, wireless connectivity options such as Wi-Fi, LoRa, or Bluetooth enable efficient remote monitoring and management of the farm [277–279].

Additionally, AI processes real-time sensor data to optimize SLF farm operations [see Figure 8]. AI-powered growth models analyze historical and real-time plant growth data to optimize nutrient cycles and predict optimal harvest times. Computer vision detects pest infestations, nutrient deficiencies, and diseases. AI also enables predictive maintenance by identifying failures in pumps, HVAC (heating, ventilation, and air-conditioning) systems, and lighting, reducing downtime. HVAC systems in SLF play a crucial role in maintaining optimal environmental conditions for plant growth [280]. In SLF setups like hydroponics, aeroponics, and vertical farming, HVAC systems regulate temperature, humidity, and air quality to enhance crop productivity and sustainability and reduce operational costs by dynamically adjusting airflow, dehumidification, and heating based on weather forecasts and plant requirements. AI-integrated HVAC systems optimize energy efficiency by changing temperature and humidity based on real-time sensor data. IoT-enabled climate control monitors CO_2 levels, ensuring plants receive optimal atmospheric conditions for photosynthesis. Innovative ventilation systems improve air circulation, preventing mold and disease outbreaks [281–283].

By integrating AI and IoT in SLF, growers can detect diseases early, manage crops precisely, and make data-driven decisions to improve yields and minimize losses. Precision agriculture ensures resource-efficient farming using automation and data analytics. AI-driven fertigation systems adjust real-time pH, EC, and nutrient composition, reducing water and fertilizer waste. Automated harvesting and sorting use AI-powered robotic arms to harvest ripe produce based on size, color, and texture. AI-based climate software-based control systems optimize LED lighting and CO_2 levels, reducing energy consumption. Advanced systems have significantly enhanced the water efficiency of SLF setups. New software platforms enable remote monitoring and control, making them ideal for large-scale operations and multi-site growers [284–286].

The deployment process of these tools involves installing IoT sensors in the greenhouse or vertical farm for real-time monitoring. Sensors connect to a cloud-based AI platform via wireless networks. AI algorithms process sensor data and predict water, nutrients, and climate control. Automated actuators adjust farm conditions such as irrigation, HVAC, and lighting. AI-powered robots and drones monitor plant health using computer vision. Farmers receive insights and alerts via a mobile app or dashboard for better decision-making [287–291].

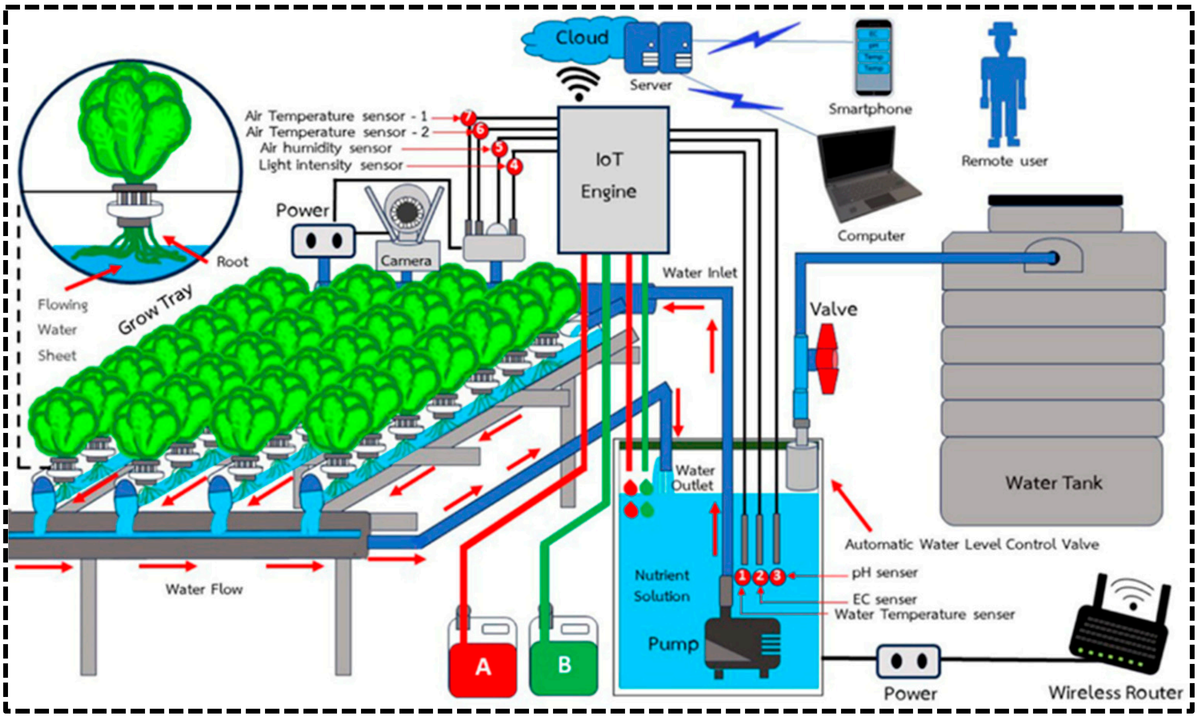


Figure 8. An intelligent farm system for hydroponic plant cultivation [292].

The information presented highlights that integrating automation and innovative farming methods in SLF represents a complex combination of advantages and challenges that merit thorough examination. On the positive side, automation and innovative horticulture tools offer unparalleled operational efficiency, resource management, and yield enhancement. Automated systems are adept at performing specific tasks, such as nutrient delivery, growth, fruit maturity detection (root system development), early disease detection, and climate regulation, reducing human error and allowing individuals to concentrate on other responsibilities. Moreover, the data-driven approach of precision farming enables prompt adjustments to various growth conditions, leading to more efficient use of input resources [293–299]. This methodology can potentially increase yield and foster a more sustainable production system by minimizing waste and its environmental impact. However, these advantages come with significant challenges that must be addressed. As previously mentioned, the initial investment required for implementing these advanced technologies and their energy demands can be considerable, creating financial barriers, particularly for smaller farmers. This situation raises questions about the broader applicability of these benefits across the agricultural landscape. It is crucial to tackle these issues efficiently and promptly to meet the urgent need for increased food production, especially given the challenges posed by diminishing arable land and the effects of severe climate change.

4. Conclusions

This review has critically examined the role of SLF systems in enhancing the resilience of horticultural production under increasing urbanization and climate stress. In addressing the guiding research questions, the study first clarified that climate resilience in agriculture refers to the ability of food systems to absorb, adapt to, and recover from climate-induced disturbances while maintaining productivity, sustainability, and resource efficiency. SLF technologies—such as hydroponics, aeroponics, and substrate culture—enhanced water-use efficiency and crop productivity by enabling soil-independent cultivation, precision nutrient management, and reduced water loss. These systems are particularly well suited for leafy greens and high-value horticultural crops grown in controlled environments, where land degradation, water scarcity, or heat stress limit conventional farming.

A comparative analysis revealed that substrate-based systems offer more flexible crop support and buffering capacity, while hydroponic and aeroponic systems maximize yield per unit area under stable conditions. In urban and peri-urban settings, SLF can localize food production by utilizing rooftops, vertical structures, and retrofitted indoor spaces—thereby reducing reliance on extended supply chains and improving access to fresh produce. However, SLF deployment faces notable barriers. High infrastructure and operational costs, energy demands, and a need for technically skilled labor limit its scalability, especially in resource-constrained regions. Integrating technologies such as AI, IoT, and automation is advancing system performance, yet their adoption remains uneven and cost-prohibitive for many communities.

In summary, SLF systems cannot substitute traditional agriculture across all contexts but serve as a strategic complement for urban horticulture and climate-sensitive zones. Their success depends on localized planning, targeted financial support, and capacity-building initiatives. Continued research and policy engagement are needed to adapt SLF technologies to broader socioeconomic settings and ensure their viability as part of resilient, future-ready food systems.

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