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Vertical Farming: innovation in pursuit of sustainable urban agriculture

Agricultura Vertical: Innovación en la búsqueda de una agricultura urbana sostenible

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ABSTRACT

Food production is a fundamental pillar of global food systems, and vertical farming (VF) has emerged as a promising strategy to address food security challenges in urban areas. This review synthesizes evidence on VF through a systematic analysis of scientific and technical literature retrieved from Google Scholar and ScienceDirect, following the PRISMA 2020 Flow Diagram methodology. The conceptual structure of the field was examined using a term co-occurrence network analysis with VOSviewer (2025). The selected studies were classified according to the environmental, economic, and social dimensions of sustainability, with emphasis on water use efficiency and energy consumption, technical and economic feasibility, and food security, respectively. The findings indicate that VF is receiving increasing global attention due to its potential to enhance urban resilience and its growing acceptance among producers and consumers. However, VF remains an emerging technology, and further research is required to improve its feasibility, particularly through reducing environmental impacts, optimizing energy efficiency, and strengthening economic performance. Strategic investments in renewable energy, smart agriculture, and water-efficient technologies will be essential to ensure the long-term sustainability and scalability of VF in urban food systems.

Keywords: Sustainable systems; food security; factory farms; modern technologies.

RESUMEN

La producción de alimentos constituye un pilar fundamental de los sistemas alimentarios globales, y la agricultura vertical (AV) ha surgido como una estrategia prometedora para abordar los desafíos de la seguridad alimentaria en las áreas urbanas. Esta revisión sintetiza la evidencia disponible sobre la agricultura vertical mediante un análisis sistemático de literatura científica y técnica obtenida de Google Scholar y ScienceDirect, siguiendo la metodología del diagrama de flujo PRISMA 2020. La estructura conceptual del campo fue examinada mediante un análisis de redes de coocurrencia de términos utilizando VOSviewer (2025). Los estudios seleccionados se clasificaron de acuerdo con las dimensiones ambiental, económica y social de la sostenibilidad, con énfasis en la eficiencia en el uso del agua y el consumo energético, la viabilidad técnica y económica, y la seguridad alimentaria, respectivamente. Los hallazgos indican que la agricultura vertical está recibiendo una atención creciente a nivel global, debido a su potencial para fortalecer la resiliencia urbana y a su creciente aceptación tanto por parte de productores como de consumidores. No obstante, la agricultura vertical sigue siendo una tecnología emergente, y se requiere mayor investigación para mejorar su viabilidad, particularmente mediante la reducción de los impactos ambientales, la optimización de la eficiencia energética y el fortalecimiento del desempeño económico. Las inversiones estratégicas en energías renovables, agricultura inteligente y tecnologías eficientes en el uso del agua serán esenciales para garantizar la sostenibilidad y escalabilidad a largo plazo de la agricultura vertical en los sistemas alimentarios urbanos.

Palabras clave: sistemas sostenibles; seguridad alimentaria; granjas industriales; tecnologías modernas.

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1. Introduction

Vertical farming encompasses a range of technologies that enable production in limited spaces through vertically arranged systems (Al-Kodmany, 2018; Kabir et al., 2023; Royston & Pavithra, 2018; Zhu & Marcelis, 2023). This concept distinguishes between two types of production systems. Song et al. (2022) describe a system operating in a fully enclosed and controlled environment, where all growth factors such as light, temperature, relative humidity, and nutrient supply are continuously monitored and artificially regulated (Figure 1). In contrast, Fernández-Cabanás et al. (2020) and Singh et al. (2015) explain that controlled-environment farming can also be implemented in greenhouse settings, where natural resources such as light, air, and temperature are utilized but may be supplemented through artificial means, including LED lighting or CO_2 enrichment, to enhance crop yield.

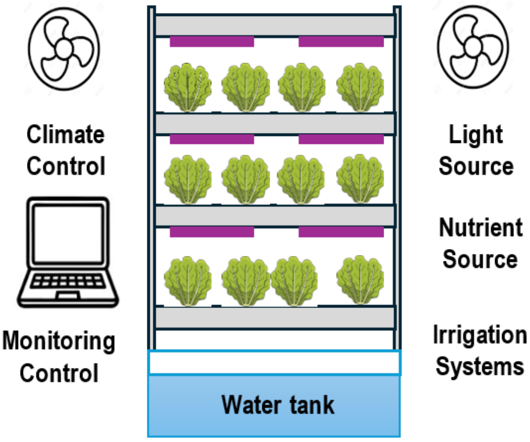


Figure 1. Stacked vertical farming systems with supplementary light-controlled environment.

Another classification within VF distinguishes between stacked horizontal systems and vertical growing surfaces. Beacham et al., (2019) defines stacked horizontal systems consist of multiple tiers of horizontally arranged growing platforms, typically located within greenhouses or fully controlled environments. In contrast, Putri et al., (2023) explains vertically growing surfaces include towers systems (Figure 2) or where lack of space can be constraint, which are often implemented to repurpose underutilized urban areas. These include indoor and outdoor sections of buildings (both occupied and abandoned), as well as rooftops, balconies, and other similar environments (D'Ostuni et al., 2022; Drottberger et al., 2023).

Figure 2. Lettuce production in a hydroponic tower system at the Fabio Baudrit Moreno Agricultural Experimental Station (EEFBM), University of Costa Rica, Alajuela province, Costa Rica, 2025.

The most employed methods for implementing VF systems include hydroponic, aquaponic, and aeroponic techniques. These approaches facilitate the efficient cultivation of a wide variety of leafy greens and other horticultural crops. In addition to supporting high productivity, they are specifically designed to minimize water consumption while enhancing both yield and food quality (Zhu & Marcelis, 2023). Each technique is characterized by the selected substrate and the absence of it in soilless systems and by the specific strategies employed for nutrient delivery. Hydroponics uses a nutrient solution composed of water and essential nutrients as the growing medium, replacing soil; an inert substrate may also be incorporated (Kalantari et al., 2018). Aquaponics utilizes wastewater from fish tanks to fertilize plants (Al-Kodmany, 2018) and aeroponics plants are suspended in the air, with their roots continuously misted with a fine spray of nutrient solution (Erekath et al., 2024).

VF is increasingly being adopted in countries such as the United States, South Korea, Japan, China, Germany, France, India, and Singapore as a strategy to enhance food security (Butturini & Marcelis, 2019; Shao et al., 2022; Van Garroway et al., 2022; Wood et al., 2020). Urban agriculture, including VF, has the potential to improve local food self-sufficiency and contribute to sustainable resilience (Gunapala et al., 2025; Karpe et al., 2025). In particular, VF offers an effective solution for ensuring a consistent supply of fresh food in peri-urban and urban areas, where access to agricultural land is limited (Eigenbrod & Gruda, 2015; Kouloumprouka et al., 2024; Shao et al., 2022; Sousa et al., 2024).

1.1 Sustainability in vertical farming systems

Sustainability, originally defined by the United Nations (1987) as the capacity to meet present needs without compromising the ability of future generations to meet their own, remains a guiding principle in agriculture and public policy. Over time, this concept has evolved into more comprehensive frameworks. For instance, Elkington (2006) introduced the triple bottom line approach, emphasizing the balance among economic, environmental, and social dimensions to achieve sustainability. According to Nogueira et al. (2023), this framework is particularly relevant for ensuring the long-term viability of agricultural systems.

More recently, the United Nations introduced the 17 Sustainable Development Goals (SDGs) in 2015 to foster global development, promote a more sustainable future, and reduce carbon emissions in alignment with the 2030 Agenda (Sorooshian, 2024). Furthermore, the recent incorporation of circular economy principles into VF practices further enhances its sustainability potential. The circular economy seeks to reduce waste, maximize resource efficiency, and minimize environmental impact while simultaneously generating economic and social value (Ferreira et al., 2018). In this context, VF can be regarded as a strategic approach to achieving sustainability by integrating resource-efficient practices and reducing environmental pressures.

Recent studies indicate that VF technologies are being developed and implemented worldwide due to their resilience under current environmental and socioeconomic conditions (Zhu & Marcelis, 2023; Song et al., 2022). Their acceptance among both producers and consumers continues to grow, as VF provides a promising alternative for ensuring food availability in urban areas where space is limited. Nevertheless, several authors emphasize that the comprehensive achievement of sustainability across environmental, social, and economic dimensions remains limited, suggesting that VF technologies still require further refinement to fully align with sustainability objectives (Fernández-Cabanás et al., 2020; Dziumla et al., 2025; Kabir et al., 2023).

The purpose of this study is to review how VF has been addressed in terms of sustainability within food systems, with particular inclusion of the Sustainable Development Goals (SDGs). The review examines key parameters that provide measurable insights into VF sustainability, including water use efficiency (WUE), energy efficiency, agricultural productivity, economic viability, and contribution to food security. These parameters were selected due to their critical role in VF. WUE ensures efficient use of controlled nutrient solutions, energy efficiency addresses the high demands of lighting and climate control, agricultural productivity evaluates yield potential in urban settings, economic viability considers feasibility and scalability, and contribution to food security reflects the system's capacity to provide reliable, nutritious food.

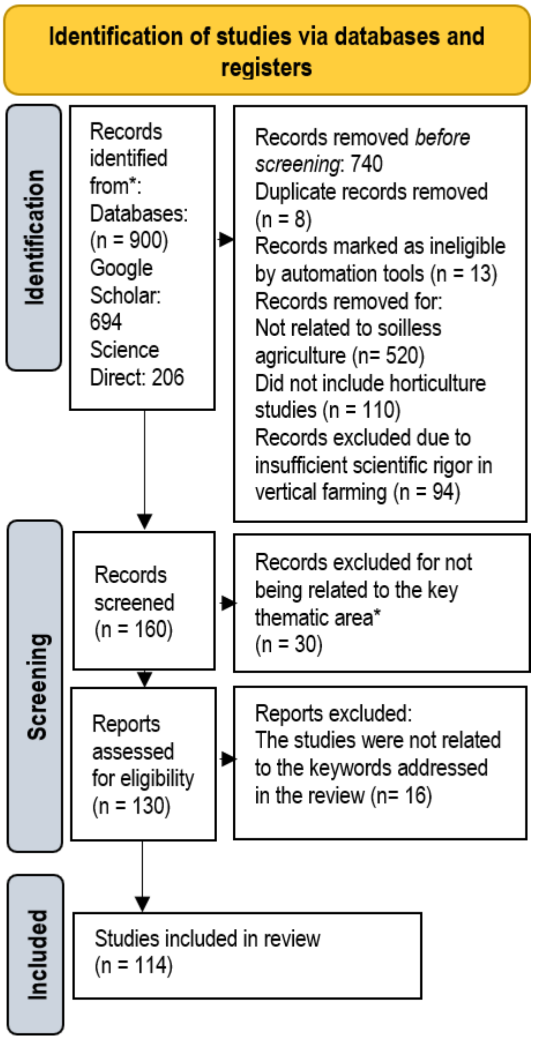
2. Methodology

The information was synthesized through a comprehensive review of scientific publications on VF. The selected studies were classified according to the environmental, economic, and social dimensions of sustainability, focusing on water use efficiency and energy consumption, technical and economic feasibility, and food security, respectively. The literature search was conducted using Google Scholar and ScienceDirect and covered the period from January 2015 to October 2025, selected to capture recent trends in VF research, following the PRISMA 2020 Flow Diagram methodology (Figure 3). The search strategy was based on combinations of keywords grouped into thematic blocks. The primary concept included terms such as *"vertical farming"*, *"plant factory"*, *"indoor farming"*, *"controlled environment agriculture"*, *"vertical crops"*, and *"vertical greenhouses"*. These were combined with sustainability-related terms, including *"sustainability"*, *"sustainable development"*, and *"circular economy"*, as well as resource-efficiency and system-related terms such as *"water use efficiency"*, *"energy efficiency"*, *"hydroponic systems"*, *"recirculating systems"*, and *"renewable energy"*. Additionally, food system and spatial context terms *"food security"*, *"urban agriculture"*, *"urban farming"*, and *"peri-urban farming"*—were incorporated into the search strategy. No geographical restrictions were applied, and only English-language sources were considered.

3. Trends on Vertical Farming

An analysis of the scientific literature reveals a consistent increase in research on VF over the past five years. The year 2024 reported the highest number of publications, while 2016 and

2017 registered the lowest. This upward trend reflects the rising academic and industrial interest in VF, largely driven by technological advancements and the growing demand for sustainable agricultural solutions (Figure 4).



**Key thematic areas: Water use efficiency, energy efficiency, economic viability, agricultural productivity and food security*

Figure 3. PRISMA 2020 Flow Diagram Methodology (adapted from Page et al., 2021).

Economic viability emerged as the most extensively researched topic in the context of VF technologies, with 39 scientific articles identified. Energy efficiency ranked second, with 23 studies highlighting the importance of environmental considerations, followed by agricultural productivity with 21 articles, and WUE, which was addressed in 15 publications. Food security was the least explored topic, with only 16 articles (Figure 5). Nevertheless, most studies emphasized the potential of VF technology as a viable food production strategy for cities.

The network visualization of co-occurrences generated using VOSviewer (2025) illustrates the conceptual structure of the research field corresponding to vertical farming. This term occupies a central position within the map, acting as the main connecting node among other relevant concepts.

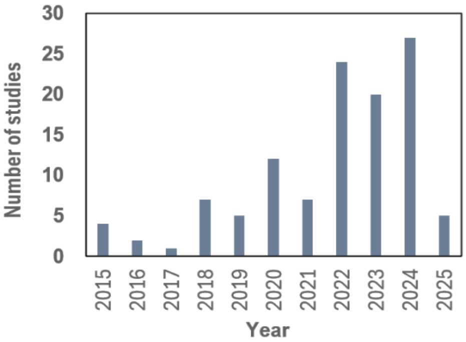


Figure 4. Number of studies in sample *(n = 114)* on vertical farming by year of publication.

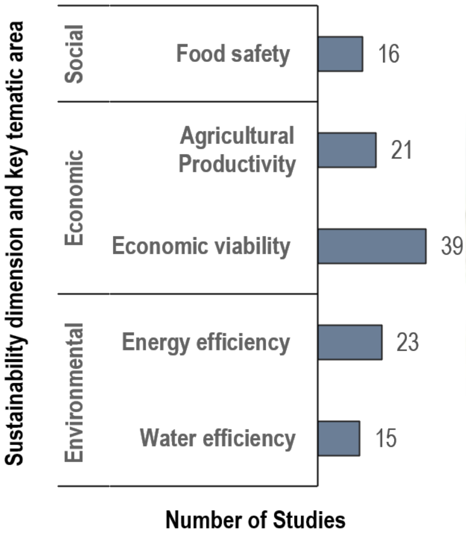


Figure 5. Number of studies *(n = 114)* on vertical farming categorized by sustainability dimensions and key thematic areas.

At least five thematic clusters can be identified: a blue cluster associated with controlled environment agriculture and automation; a yellow cluster related to urban agriculture and environmental sustainability; a red cluster focused on hydroponic and aeroponic systems; a green cluster linked to circular economy and energy efficiency; and a purple cluster oriented towards sustainability and urban development. The density of interconnections among these clusters highlights the growing integration of sustainability, technological innovation, and food production in controlled urban environments, thus reflecting the interdisciplinary evolution of the research field in the analyzed studies (Figure 6).

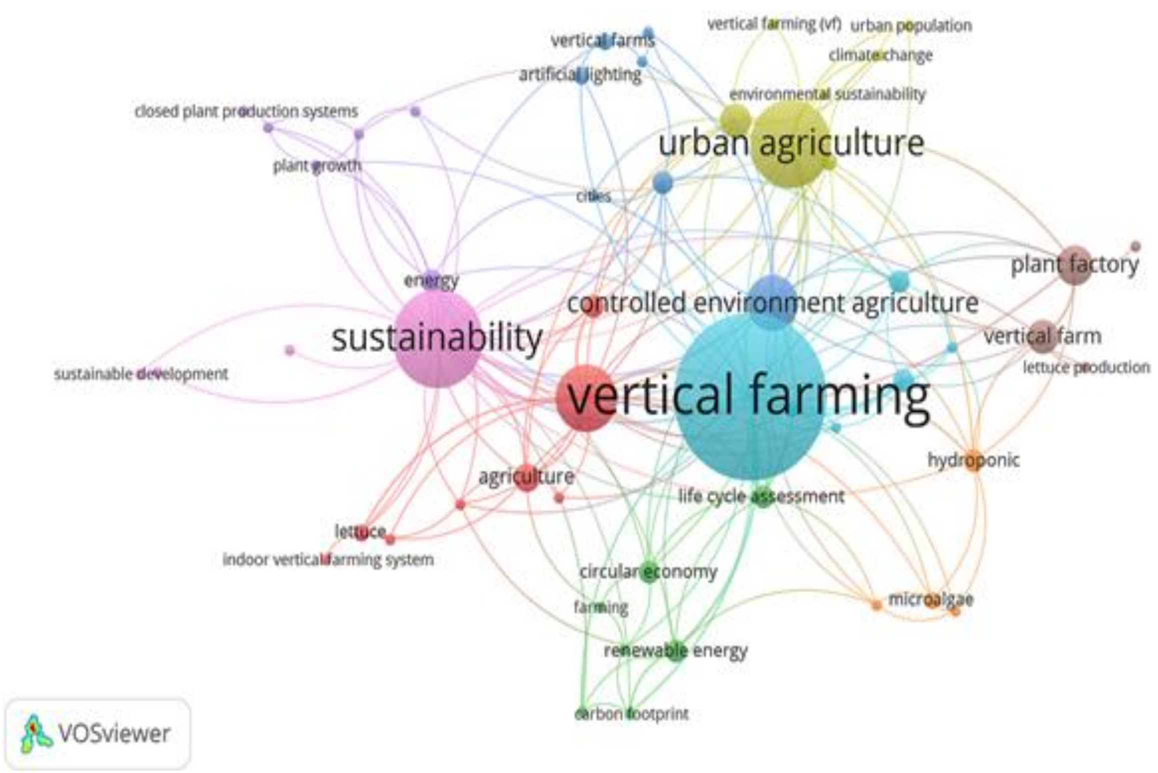


Figure 6. Co-occurrence network of key words in vertical farming studies.

3.1 Sustainability in vertical farming: opportunity or challenge?

Sustainability in VF has traditionally been assessed through indicators related to productivity, environmental impact, energy consumption, and water use efficiency (Bunge et al., 2022; Barbosa et al., 2015; Carotti et al., 2023) (Table 1). While environmental metrics, such as water and fertilizer use efficiency, energy demand, and greenhouse gas emissions, provide insights into resource efficiency and ecological impact, studies have highlighted significant variability depending on system design, lighting strategies, and crop management (Blom et al., 2022; Avgoustaki & Xydis, 2021; Joensuu et al., 2024).

Table 1
Sustainability Indicators for productivity assessment in Vertical Farming Systems

Dimension	Related SDGs*	Key thematic area	Indicators and unit/measure
Environmental Dimension	SDG 7: Affordable and Clean Energy SDG 12: Responsible Consumption and Production	Water use efficiency *(including aspects related to nutrient solution)	Water use efficiency (WUE): grams of fresh weight per liter of water (g L^{-1} H_2O) Fertilizer use efficiency: grams of applied fertilizer per kilogram of product (g kg^{-1}) Water pollution: phosphate equivalents (kg PO_4^{3-} eq) or nitrogen equivalents (kg N eq)
		Energy efficiency	Energy consumption: kilowatt-hours per production cycle (kWh/cycle) Greenhouse gas (GHG) emissions: kilograms of CO_2 equivalent (kg CO_2-eq)
Economic Dimension	SDG 8: Decent Work and Economic Growth	Economic viability	Unit production cost (USD kg^{-1}); production and operational costs; return on investment (ROI, %)
		Agricultural productivity	Crop yield: kilograms produced per crop (kg/crop) or per year (kg m^{-2}·$year^{-1}$)
Social Dimension	SDG 2: Zero Hunger SDG 3: Good Health and Well-being	Food security	Number of jobs generated Consumer acceptance–based quality assessment. Content of bioactive compounds (mg/100g)

**SDGs: Sustainable Development Goals.*

Economic indicators, including unit production cost, return on investment, and sustainable productivity, have been shown to be strongly influenced by technological choices, automation level, and energy optimization strategies (Arcasi et al., 2024; Akinmeji et al., 2021).

Social dimensions, such as consumer acceptance, employment generation, and access to fresh local produce, are increasingly recognized as critical for the broader adoption and legitimacy of VF systems within urban contexts (Specht et al., 2016; Jürkenbeck et al., 2019; Oh & Lu, 2023). Integrative approaches, including composite sustainability scores, life cycle assessment, and system resilience frameworks, have proven valuable in capturing trade-offs and synergies across environmental, economic, and social dimensions, enabling a more holistic understanding of VF sustainability (Gargaro et al., 2024; Dziumla et al., 2025; Wu et al., 2025). Such comprehensive evaluation frameworks not only facilitate monitoring and comparison of vertical farming systems but also provide practical guidance for researchers, practitioners, and policymakers seeking to enhance sustainable urban agriculture.

Research highlights VF's contributions to Sustainable Development Goals (SDGs) 7, 12, and 13 by promoting energy efficiency and reducing environmental impacts. From an economic perspective, studies have examined production efficiency and profitability, generation of employment opportunities, and the stimulation of economic growth, in alignment with SDG 8: Decent work and economic growth (Jürkenbeck et al., 2019). In terms of the social dimension, VF supports SDGs 2 and 3 by enhancing food security and public health through improved access to fresh, nutritious foods (Table 2). Each of these parameters will be detailed in the subsequent sections.

Table 2
Strategic proposals for enhancement of the Sustainability Dimensions and their SDGs across key thematic areas of Vertical Farming (n=71)

Environmental Dimension: *SDG7: Affordable and Clean Energy, SDG 12: Responsible Consumption and Production		
Key thematic area	**Stategic proposal**	**References**
Water use efficiency	Recirculation technologies	Rufí-Salís et al., 2020
	Biomass maximization: using fewer liters of water in production systems	Carotti et al., 2023; Orsini et al., 2020; Regmi et al., 2024
	Rainwater harvesting	Erekath et al., 2024
	Reduction of the amount of water and fertilizers that are disposed	Cowan et al., 2022; Joensuu et al., 2024
	Reduction of nitrogen and phosphorus footprint	Gargaro et al., 2024; Huo et al., 2020; Liu et al., 2022; Ljumović et al., 2024
	Microorganism use: addressing eutrophication, treating hydroponic waste, and promoting plant growth.	Dhawi, 2023; Ergun et al., 2020; Lee & Lee, 2015; Mei et al., 2023; Plocek et al., 2024; Renganathan et al., 2024
Energy efficiency	Development of energy efficient and Vertical Farming systems.	Arabzadeh et al., 2023; Avgoustaki & Xydis, 2021; Blom et al., 2022; de Carbonnel et al., 2022; Gillani et al., 2022; Kaiser et al., 2024; Song et al., 2022
	Advances in intermittent lighting technologies: reducing energy consumption.	Avgoustaki et al., 2021; Blom et al., 2024; Filatov et al., 2022; Jin et al., 2023; Olvera-González et al., 2021; Osman et al., 2024; Pereira & Gomes, 2025; Sena et al., 2024; Sipos et al., 2021; Wong et al., 2020
	Incorporation of clean alternative energy sources	Cossu et al., 2023; Gargaro et al., 2024; Kobayashi et al., 2022; Tablada et al., 2020
Economic Dimension: SDG 8: Decent work and Economic growth		
Economic viability	Cost reduction	Akinmeji et al., 2022; Arcasi et al., 2024; Jamil et al., 2024; Mir et al., 2022; Rajan et al., 2019; Sandison et al., 2023
Agricultural productivity	Technology and optimization: enhancing production systems for different crops and maximizing space	Fernández-Cabanás et al., 2020; Kang et al., 2024; Nájera et al., 2022; Naranjani et al., 2022; Ng et al., 2023; Majid et al. 2021; Rao et al., 2020; Rathor et al., 2024; Shomefun et al., 2018; Siregar et al., 2022; Touliatos & Mcainsh, 2016; Wicharuck et al., 2023; Kouloumprouka et al., 2024
	Biodegradable substrates	Erekath et al., 2024; Jia et al., 2024
Social Dimension: SDG 2: Zero Hunger, SDG 3: Good Health and Well-being		
Food security	Food security, urban agriculture, production of antioxidant-rich foods, functional food, increased food quality and safety, and reduced agrochemical use.	Al-Chalabi, 2015; Al-Kodmany, 2018; Despommier, 2024; Eigenbrod & Gruda, 2015; Kalantari et al., 2018; Rao et al., 2022; Shao et al., 2022; Specht et al., 2016; Świąder et al., 2023; Sousa et al., 2024; Vatistas et al., 2022; Wood et al., 2020

**SDGs: Sustainable Development Goals.*

3.2 Water use efficiency: optimizing resources for a sustainable future

The concept of WUE is defined as the amount of water required to produce a given quantity of biomass (Carotti et al., 2023). VF technologies promote WUE by optimizing irrigation practices and improving fertilizer management. According to Regmi et al. (2024) water consumption is influenced by several factors, including crop type, cultivar, environmental conditions, and production system.

Accurate assessment of water use in vegetable production is essential for identifying opportunities to reduce environmental impact and to support the development of circular economy and sustainable agricultural practices. VF technologies have demonstrated significant potential for water savings, with reported reductions ranging from 40% to 70% compared to conventional agriculture (Naqvi et al., 2022; Rufí-Salís et al., 2020). In addition, the strict control of production parameters in VF systems contributes to reduced food waste compared to traditional farming methods (Pinstrup-Andersen, 2018).

Production systems are classified into two main categories based on nutrient solution management: open and closed. Open systems discard the nutrient solution after a single use, resulting in higher water and nutrient consumption (Figure 7A). In contrast, closed systems such as most VF applications, recirculate and reuse nutrient solutions, thereby optimizing resource use and minimizing environmental impact (Figure 7B).

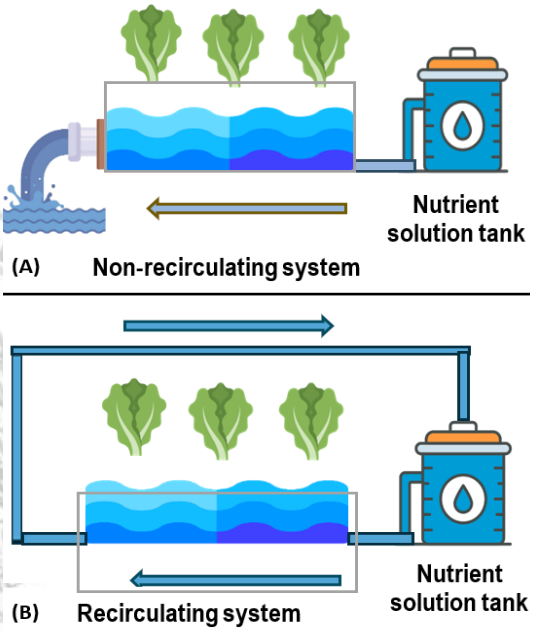


Figure 7. Classification of hydroponics production systems. A). open-loop hydroponic system. B). close-loop hydroponic system.

A prominent example of this technique is the Nutrient Film Technique (NFT), where a thin film of nutrient solution continuously flows over plant roots (Khan, 2018).Closed-loop systems in VF technologies use hydroponics, aeroponics, and aquaponics methods to primarily recirculate and reuse nutrient solutions, optimizing water and nutrient efficiency (Kumar et al., 2021). In a recirculating prototype, such as vertically growing towers, an integrated internal irrigation system ensures continuous contact between roots and the nutrient solution. These systems employ low-energy pumps to maintain a steady circulation of the fertigation solution from the storage tank (Touliatos et al., 2016).

Studies estimate that WUE for lettuce cultivation under controlled conditions ranges from 45 to 80 grams of fresh weight per liter of water ($g\ L^{-1}\ H_2O$) (Orsini et al., 2020), positioning it as a highly efficient system due to environmental control. In a comparative study of controlled vertical hydroponic floating-root and aeroponic systems for lettuce production, the reported WUE values was 28.1 and 52.9 $g\ L^{-1}\ H_2O$, respectively (Carotti et al., 2023). Other findings indicate that, in greenhouse and open-field systems, average WUE values are estimated to range between 5-60 $g\ L^{-1}\ H_2O$ and 3-20 $g\ L^{-1}\ H_2O$, respectively (Barbosa et al., 2015).

In terms of fertilizer efficiency, open systems achieve around 68%, while closed systems can reach up to 85% (Khan, 2018). In aeroponic systems, water consumption tends to be lower, because plant roots are suspended in air, and nutrients are supplied through mist or spray irrigation at constant intervals, preventing root desiccation or anoxia (Fasciolo et al., 2023). However, the higher initial investment cost associated with aeroponics, compared to conventional hydroponic systems, remains a limiting factor for its widespread adoption (Van Gerrewey et al., 2022).

Technological advancements have facilitated the use of treated water from rainwater harvesting systems and minimally contaminated wastewater, primarily aimed at conserving freshwater resources (Erekath et al., 2024). Nonetheless, the disposal of hydroponic nutrient solutions has raised environmental concerns, particularly regarding water pollution from excess nutrients, such as nitrogen and phosphorus, which can lead to eutrophication (Gargaro et al., 2024; Renganathan et al., 2024; Rufí-Salís et al., 2020). However, recycling nutrients in VF systems has been shown to significantly reduce nutrient footprints by approximately 37% for nitrogen (N) and 36% phosphorus (P), primarily due to the reuse of nutrients in fertigation and a less frequent of solution replacement.

Recirculation practices in VF systems can reduce the risk of eutrophication by 70% to 90% compared to open-field agricultural systems (Joensuu et al., 2024; Van Gerrewey et al., 2022). Nitrogenous compounds, such as nitrous oxide (N_2O), nitrates (NO_3^-), and ammonia (NH_3), are managed and quantified more efficiently in VF due to the implementation of precise monitoring and control mechanisms. In contrast, conventional agriculture often lacks such rigorous systems, resulting in less efficient nutrient management (Liu et al., 2022).

Ensuring water quality is essential for the sustainability of VF systems. Several strategies have been proposed to mitigate eutrophication risks, including the integration of microalgae species such as *Chlorella vulgaris* into recirculating nutrient solutions to treat residual compounds (Ergun et al., 2020; Ljumović et al., 2024). These microalgae not only enhance oxygen availability but also act as biostimulants at appropriate concentrations, promoting plant growth and reducing the concentration of chemical nutrients such as N and P, two of the primary contributors to environmental degradation (Cowan et al., 2022). Although such strategies have been shown to improve water and nutrient use efficiency, some studies have reported growth inhibition in specific crops, such as arugula (*Eruca sativa*), when exposed to high concentrations or prolonged exposure to microalgae (Huo et al., 2020).

The application of microorganisms to hydroponic systems is a well-established and extensively studied area. Genera such as *Pseudomonas*, *Bacillu*s, *Enterobacter*, and *Streptomyces* have been identified for their effectiveness in pathogen control, particularly in continuous circulation systems (Lee & Lee, 2015). In addition to their biocontrol properties, these microorganisms have been shown to reduce abiotic stress in plants and enhance plant immunity (Dhawi, 2023). Specifically, *Pseudomonas psychrotolerans* has been reported to promote lettuce growth in vertical NFT and floating root systems under greenhouse conditions (Mei et al., 2023), while *Bacillus amyloliquefaciens* has demonstrated positive effects as a biofertilizer (Plocek et al., 2024).

3.3 Energy efficiency: innovative approaches for saving energy

The complexity of VF systems poses challenges for direct comparisons across studies. Al-Qubati et al. (2024) argue that urban food production can help reduce greenhouse gas (GHG) emissions by minimizing transportation requirements; however, Beacham et al. (2019) note that transportation accounts for only about 11% of agriculture's total GHG emissions. Moreover, VF facilities can substantially contribute to emissions due to their high energy demands, low electrical efficiency, and, in some cases, limited integration of renewable energy sources. As highlighted by Parkes et al. (2023), further research is needed to develop strategies that effectively reduce the overall carbon footprint of VF systems.

The primary challenge to achieving sustainability in VF is its high energy demand (de Carbonnel et al., 2022), despite ongoing advancements in the energy efficiency of components such as LED lamps. Artificial lighting alone accounts for approximately 65% to 80% of total energy demand (Avgoustaki & Xydis, 2021; Blom et al., 2022). Energy consumption also varies by system prototype, for example, in a Nutrient Film Technique (NFT) system used for lettuce cultivation in a controlled environment with LED supplementation, energy consumption reached 30.15 kWh per lettuce plant over five weeks, compared to 36.5 kWh in a floating root system. Specifically, for water circulation, the NFT system required 9.22 kWh, whereas the floating root system consumed 4.15 kWh (Gillani et al., 2022).

In vertical greenhouse horticulture, artificial lighting can supplement daily photon requirements to enhance photosynthetic activity. These systems generally exhibit higher energy efficiency compared to controlled indoor environments, primarily due to the reliance of natural light (Vatistas et al., 2022). Nevertheless, reported energy consumption associated with supple-mented lighting varies significantly across studies and system prototypes. For instance, one study reported an energy use of 0.02 kWh per kilogram for leafy vegetable production in stacked horizontal systems (Song et al., 2022), while another documented 3.72 kWh per kilogram for basil biomass production in a greenhouse in towers (Pereira & Gomes, 2025).

Despite the high energy demand, efficient lighting in controlled environments can substantially enhance biomass production, increase dry matter accumulation, and shorten crop growth cycles, particularly in crops such as lettuce (Jin et al., 2023). As a result, operational VF companies have optimized artificial lighting through precise spectral adjustments. Furthermore, studies have identified optimal light durations for various crop types, thereby minimizing unnecessary energy use by eliminating redundant lighting periods (Delorme & Santini, 2022).

Fluorescent lights systems have largely been replaced by light-emitting diode (LED) lamps to improve production efficiency and reduce both environmental impact and carbon footprint (Sena et al., 2024). In addition, LED light has been shown to improve flavor, enhance nutritional quality, and extend the shelf life of commercial horticultural products. Recent research increasingly focuses on determining the specific photon requirements for various crops and evaluating the effects of far-red wavelengths (FR, 700–750 nm) on plant morphology and metabolism (Carotti et al., 2024). Furthermore, studies are investigating the role of blue light wavelengths in increasing phytonutrient content, as well as the inhibitory effects of green light on plant growth (Wong et al., 2020). Modern LED lamps are highly dynamic, allowing for the adjustment of photon spectra and intensities based on specific requirement of each crop.

A current strategy to reduce electricity consumption in controlled environments involves adjusting the photoperiod according to crop-specific requirements (Kaiser et al., 2024). Experimental studies have demonstrated that strategically selecting dark periods and intermittent lighting regimes can reduce artificial lighting costs by 14% to 26% per month throughout the year, without negatively affecting basil plant development, quality, or yield (Avgoustaki et al., 2021; Blom et al., 2024). These findings are consistent with other research suggesting that scheduling energy use during off-peak electricity hours can result in cost savings of 5% to 30% (Arabzadeh et al., 2023). However, some studies have reported no significant differences in plant performance between continuous and intermittent LED lighting strategies (Olvera-González et al., 2021).

In basil cultivation, the conventional 16-hour light and 8-hour dark photoperiod was modified to a 14-hour light period, supplemented by a redistribution of dark hours and brief 10-minute intervals of intermittent light during dark phase. This approach was positively associated with enhanced tolerance to abiotic stress (Filatov et al., 2022). Although the method did not significantly affect the crop's overall physiological response, exposure to intermittent light patterns resulted in a 47% increase in biomass production and reduced electricity consumption compared to continuous photoperiod lighting, positioning it as a more cost-effective strategy (Avgoustaki & Xydis, 2021).

Studies suggest that VF can improve efficiency and sustainability through the integration of renewable energy sources, such as photovoltaic cells (Cossu et al., 2023; Jamil et al., 2024; Zhu & Marcelis, 2023). Despite significant advancements in LED lighting technology, energy consumption remains a major concern, particularly when electricity is derived from non-renewable sources (Martin et al., 2023; Skarżyński & Wiśniewski, 2024). A study conducted in the United Kingdom concluded that, depending on the energy source, the environmental impact of VF can be comparable to, or even lower than, that of a conventional agriculture (Gargaro et al., 2024). However, some researchers content that VF may never match the energy efficiency of greenhouse production, which primarily relies on natural sunlight (Stanghellini & Katzin, 2024).

Green hydrogen has emerged as a promising alternative energy source for VF (Despommier, 2024). As a clean energy option, it emits only water vapor and produces no harmful pollutants. Additionally, the water electrolysis process used to generate green hydrogen yields green oxygen as a byproduct. Recent research suggests that this oxygen, often considered a waste, can be repurposed within the VF system by incorporating it into the nutrient solution. Increasing the saturation of pure oxygen, rather than relying solely on ambient air, has been shown to enhance root efficiency and reduce the risk of fungal infections (Osman et al., 2024), which area a serious problem in closed water production systems.

3.4 Economic viability: investing in the future of urban agriculture

The costs associated with VF technologies vary depending on the specific system implemented, making accurate costs estimation complex. Nevertheless, high operational costs remain a significant challenge in controlled environments. A decade ago, studies underscored the limited research on the economic and productive feasibility of VF systems (Al-Chalabi, 2015). Although substantial progress has been made sense then, especially in terms of sustainability and energy efficiency through advancement in lighting technologies, several challenges persist.

In addition to technological considerations, costs are also influenced by factors such as crop selection, which is a key aspect shaped by market demand and consumer preferences (Jürkenbeck et al., 2019). The pricing of vegetables grown in vertical farms, especially those cultivated in controlled environments, remains a largely underexplored and unregulated area. A noticeable discrepancy persists between the pricing of vertically farmed foods and their competitiveness compared to conventionally produced alternatives (Gurung et al., 2024).

In this context, crops that require minimal maintenance, offer high added values, and demonstrate greater nutrient and WUE are considered the most suitable for VF systems (Rajan et al., 2019). Leafy greens and herbs are among the most profitable options, although the economic viability of crops such as tomatoes, bell peppers, and strawberries has also been reported (Lubna et al., 2022). Additionally, a growing market has emerged around the commercialization of microgreens, which are valued for their high concentrations of phytonutrients, antioxidants, and carotenoids (Ciuta et al., 2021; Rajan et al., 2019). However, while techniques such as hydroponics can significantly increase yields, they are also associated with higher energy consumption, which results in elevated costs (Barbosa et al., 2015).

The main disadvantage of establishing and operating VF facilities under controlled conditions is the high electricity cost, which accounts for approximately 91% of the total carbon footprint (Arcasi et al., 2024; Sandison et al., 2023). On the other hand, reduced pesticide use contributes to lower agronomic management costs compared to conventional open-field agriculture, which remains vulnerable to climate variability and potential yield losses (Mir et al., 2022). In contrast, controlled environment and greenhouse production system enable continuous, year-round cultivation.

3.5 Agricultural productivity: maximizing growth and quality

The objective of VF technologies extends beyond food production. Adding value within the agricultural industry has become increasingly important and serves as a key market differentiator. Recent research focuses on optimizing environmental factors such as light, temperature, and nutrient availability to enhance metabolic profiles of crops. This approach aims to maximize the concentration of bioactive compounds, including antioxidants, vitamins, and minerals, which offer significant health benefits (Sharathkumar et al., 2020). The related concept is associated with functional foods, where healthy lifestyles, health promotion and disease prevention are important as well as the nutritional value of the food.

Research on VF has demonstrated increased vegetable production per unit area and a shorter crop cycle compared to conventional cultivation methods (Touliatos et al., 2016). For instance, lettuce production density in vertical systems is reported to be 1.5 times higher than in a horizontal system (Wicharuck et al., 2023). Additionally, VF enhances photosynthetic efficiency and results in higher concentrations of soluble solids, protein, and crude fiber, thereby improving the nutritional quality of the produce (Akinmeji et al., 2022; Majid et al., 2021). These outcomes are achieved through the strategic use of total or supplemental LED lighting, with adjustments to light quality, spectrum, and intensity tailored to the specific of each crop (Nájera et al., 2022).

Ensuring food safety in VF systems requires the use of clean, inert and safe substrates with suitable physical and chemical properties to minimize the risk of pathogen contamination. Moreover, VF systems typically require fewer chemical inputs for pest and disease control. Recent research has focused on development of biodegradable substrates, including studies on the application of chitosan (Jia et al., 2024). Hydrogels, another promising class of biomaterials, have shown potential for distributing nutrients in response to specific concentration gradients (Erekath et al., 2024).

Modern electronic technologies have enabled the development of smart systems based on the Internet of Things (IoT) to automate VF in both greenhouses and controlled environments (Modu et al., 2020; Ng et al., 2023; G. Rao et al., 2020). These systems contribute to optimizing water and electricity usage, enable early disease detection, and thereby enhance both operational efficiency and overall sustainability (Rathor et al., 2024). The devices regulate irrigation based on optimal threshold values, activating only when necessary (Shomefun et al., 2018) and can integrate artificial intelligence according to the specific needs of the plant and production system (Siregar et al., 2022). Recent advancements in design technologies have also facilitated the integration of advanced tools, such as computational fluid dynamics (CFD), to evaluate the performance of prototypes and controlled environments within VF systems and greenhouses (Kang et al., 2024; Naranjani et al., 2022). Wu et al. (2025) suggest that integrating fluid mechanics into system design can optimize performance and enhance plant production. CFD simulations allow scenario modeling to analyze fluid dynamics across different production levels and detect ventilation inefficiencies. Moreover, they offer detailed insights into environmental conditions, water and nutrient consumption patterns, and their impact on plant development and yield (Agati et al., 2024). These accurate, data-driven models enhance predictive capacity and support strategic decision-making regarding system optimization and productivity.

3.6 Food Security: building solutions for today and tomorrow

Rapid population growth, urban expansion, carbon footprint concerns, and the limited availability of arable land presents global challenges to ensuring food access for both current and future generations (Fróna et al., 2019; Kabir et al., 2023; Oh & Lu, 2023). VF has the potential to strengthen urban and peri-urban agriculture (Yuan et al., 2022), which plays a crucial role in social well-being and enhancing food security (Eigenbrod & Gruda, 2015; Rao et al., 2022; Specht et al., 2016). Nevertheless, the long-term sustainability of VF remains a subject of ongoing debate (Bao et al., 2024; Lee et al., 2024). Integrating VF into urban planning is currently being explored as a strategy to regenerate urban spaces and promote greener, more resilient cities (Tablada et al., 2020; Toku et al., 2024).

The primary contribution of VF is its ability to maximize food production in limited spaces, making it a key factor in ensuring food security in a world where arable land is increasingly scarce and populations are concentrating in large urban centers (Kalantari et al., 2018; Zhu & Marcelis, 2023). Moreover, according to Dziumla et al. (2025), the social dimension remains the least studied and is rarely integrated with environmental or economic dimensions, with social acceptance being the most frequently analyzed indicator.

This model fosters the development of innovative production technologies within controlled or protected environments, thereby mitigating the effects of climate change and reducing the incidence of pests and diseases, consequently lowering the need for chemical interventions (Velazquez-Gonzalez et al., 2022). Among the most notable advantages of VF are its high resource use efficiency and the reduced dependence on agrochemicals, both of which represent significant steps toward more sustainable agriculture and a safer food supply (Benke & Tomkins, 2017).

Food security is important for society, but consumers are going further. As citizens become more aware of complex food with nutritional value (Swiader et al., 2023), to produce functional food is not only possible but an opportunity for the VF industry. To prevent disease and the feeling of well-being that comes from a healthy diet are targets to an increasing part of the population. Nowadays leafy vegetables and microgreens are the most commercially successful crops, but technically vertical farming allows the cultivation of many other functional foods, from medicinal plants and micronutrient fortification in food crops that have high value, including herbs, fruiting crops, root vegetables, grains, cereal and tuber crops (Oh & Lu, 2022).

4. Current and future challenges

The analysis indicates that numerous studies recognize VF as a strategic approach to enhancing food security, particularly in peri-urban and urban areas (Gunapala et al., 2025; Gurung et al., 2024; Oh & Lu, 2023). As these technologies continue to evolve, careful assessment of their technical complexity and operational reliability is essential to ensure long-term sustainability and to promote equitable access across diverse agricultural contexts and countries (Bunge et al., 2022; Dziumla et al., 2025). Evidence suggests that VF represents a paradigmatic shift in modern horticultural production; however, a systematic integration of parameters to effectively address the increasing demand for high-yield, sustainable systems that meet consumer expectations for food safety, nutritional and functional quality, and environmental sustainability remains lacking (Benke & Tomkins, 2017; Pinstrup-Andersen, 2018; Sharathkumar et al., 2020) (Figure 9).

These technologies exhibit considerable potential as sustainable and efficient food production methods, particularly when their added value is taken into account (Al-Kodmany, 2018; Barbosa et al., 2015; Carotti et al., 2023). Nevertheless, significant challenges remain, with energy consumption and high initial infrastructure investment representing two of the most critical constraints (Avgoustaki & Xydis, 2021; Delorme & Santini, 2022; Stanghellini & Katzin, 2024). Further research is required to improve the global feasibility and accessibility of VF, particularly regarding operational costs, scalability, and context-specific adaptation. A comprehensive assessment of VF sustainability should integrate a wide range of factors, including environmental impact, urban land-use pressures, social equity, technological complexity, crop diversification potential, and economic viability (Dziumla et al., 2025; Rao et al., 2022; Bunge et al., 2022). As identified in previous studies, research on the social dimensions of VF remains limited, primarily focusing on consumer acceptance, with scant evidence on the actual impacts of VF beyond its potential to produce high-quality food and generate employment (Bunge et al., 2022; Dziumla et al., 2025; Rao et al., 2022). Comprehensive evaluations of VF's social implications are largely absent, which is critical for a holistic understanding of its sustainability. In contrast, most studies focus on environmental aspects, which is understandable given the high carbon footprint associated with the energy demands of these technologies (Avgoustaki & Xydis, 2021; Delorme & Santini, 2022; Stanghellini & Katzin, 2024). Energy consumption is a key challenge, particularly in hydroponic and aeroponic systems, and largely determines the environmental sustainability of VF (Barbosa et al., 2015; Al-Kodmany, 2018; Carotti et al., 2023).

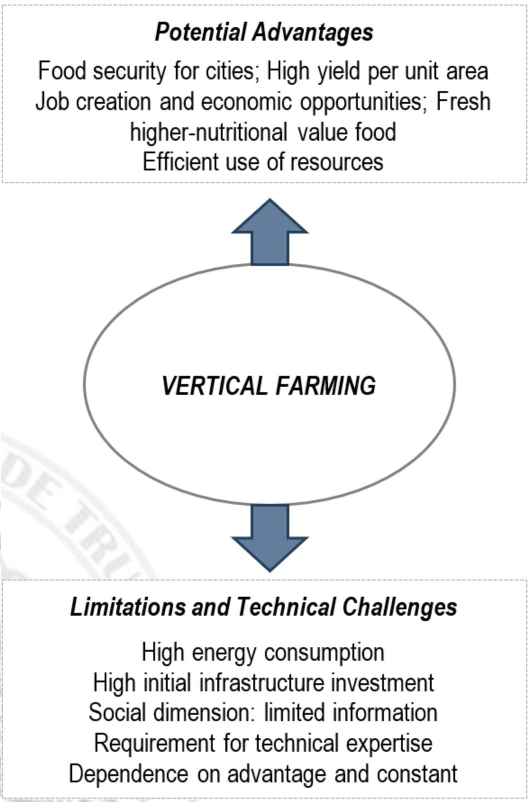


Figure 9. Key advantages and limitations of vertical farming in the pursuit of sustainability.

The development and adoption of renewable energy systems in VF, together with water-saving smart technologies, are essential for broader implementation (Arabzadeh et al., 2023; Bao et al., 2024; Gargaro et al., 2024). The use of closed systems significantly enhances water use efficiency by enabling precise control over irrigation and nutrient delivery, thereby reducing water consumption and optimizing resource management (Rufí-Salís et al., 2020; Carotti et al., 2023; Majid et al., 2021). Additionally, the integration of biological approaches, such as bioinputs, advanced nutrient management, and water recycling, supports the development of resilient and resource-efficient agricultural systems (Dhawi, 2023; Mei et al., 2023; Ljumović et al., 2024).

Despite advances in energy efficiency, the economic viability of VF remains constrained by high operational costs, particularly in energy-intensive systems, with costs varying according to the level of technology employed and across countries (Arcasi et al., 2024; Avgoustaki et al., 2021; Gillani et al., 2022). While leafy greens have shown potential profitability in VF systems, broader adoption depends on consumer acceptance, a social dimension that requires further investigation (Jürkenbeck et al., 2019; Benke & Tomkins, 2017). A relevant issue that has not been adequately addressed in the literature is the price differential between conventionally grown products and those produced through VF systems. The lack of analysis in this regard represents a limitation of current studies and simultaneously highlights a potential avenue for future research.

Nonetheless, VF presents key advantages over conventional agriculture, including opportunities to reduced pesticide use and year-round production, thereby supporting more resilient and sustainable food systems while contributing to food security and the provision of safe, high-quality products (Touliatos et al., 2016; Al-Chalabi, 2015; Fróna et al., 2019).

5. Conclusions

The analysis of 114 studies demonstrates the increasing attention devoted to vertical farming as a potential strategy for advancing sustainable food production. Nevertheless, the literature remains largely concentrated on environmental performance, particularly resource-use efficiency, with energy consumption and efficiency consistently identified as critical determinants of system feasibility and environmental sustainability. This predominant focus underscores the need for integrative assessment frameworks that systematically incorporate economic and social dimensions, enabling a more holistic evaluation of sustainability outcomes across diverse technological configurations and spatial contexts. Notably, the social dimension is comparatively underexplored, with existing studies primarily addressing consumer perceptions and product acceptance. Future research would benefit from interdisciplinary approaches that explicitly examine social indicators such as labor conditions, community engagement, equity, and social well-being, thereby strengthening sustainability assessments and informing the responsible development and governance of vertical farming systems.

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