Greenhouse Plant Production Journal 3(1) (2026) 16-30 gppj.araku.ac.ir

Greenhouse Plant Production Journal

Vertical farming: A review on greenhouse and plant factory approaches

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Review Article

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Citation: Almasian, Yasaman, Roosta, H.R. 2026. Vertical farming: A review on greenhouse and plant factory approaches. Greenhouse Plant Production Journal 3(1): 16-30.

https://doi.org/10.61882/gppj.3.1.16

KEYWORDS

Vertical farming
Plant factory
Greenhouse
Light spectra

ABSTRACT

Vertical farming is being considered as a viable solution to the significant international issues, such as the decrease in arable land, freshwater shortage, and the necessity to produce food in a consistent and high standard. Despite the wide range of studies carried out on vertical farming systems, the existing reviews tend to consider vertical greenhouses and fully controlled plant factories independently and do not provide an integrated and recent comparison between the two systems. The purpose of this review, thus, is to thoroughly examine the concept of vertical farming by answering the following major questions (i) what are the differences between vertical greenhouses and plant factories in their water and energy consumption? (ii) how productive and land-use beneficial are each system? (iii) what are the technological, economic and environmental barriers to their broader adoption? The review provides the answers to these questions through the synthesis of recent developments, and especially innovations in the areas of artificial intelligence, the Internet of Things (IoT), lighting systems, and integration of renewable energy sources. Vertical greenhouses are considered to be hybrid systems, which blend natural sunlight with additional lighting to increase space-use efficiency, as opposed to plant factories that are appraised as totally regulated systems that can produce highly predictable and uniform yield. The review incorporates the most recent technological, environmental and economic knowledge to give a critical and modern view on the present performance, challenges and future prospects of the vertical farming systems.

ARTICLE HISTORY

Received: 04 October 2025
Revised: 17 December 2025
Accepted: 05 January 2026

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Publisher: Arak University

1. Introduction

Vertical farming idea was a notion that arose in the early 2000s to offer solutions to the world problems of increasing urbanization and an escalating lack of arable land (Despommier, 2010). Limited natural resources and climatic changes are putting an ever-increasing strain on traditional agriculture, which is providing a rising demand on sustainable food production. Vertical farming is an innovative solution to providing food products sustainably in urban settings due to the opportunity to produce crops in limited areas with the help of controlled atmospheric conditions in the meantime (Benke and Tomkins, 2017; Kalantari et al., 2017a). In the given discipline, two primary systems are identified, including traditional vertical farming and plant factories (PFs), which are different in structure and capital investment only. These systems have been studied individually in most studies with very little systematic, quantitative comparisons, which is a key gap in the existing literature in future studies. Thus, the goal of the review is to make organized and comparative analysis of traditional vertical farming and plant factory systems, their advantages, disadvantages, and research and practice opportunities.

2. Soilless cultivation

Soilless cultivation is a form of sustainable farming in which plants are grown in the absence of natural soil and instead, they are grown in inert media (coco peat or rock wool) or nutrient-enriched water media. Such a technique enables the accurate control of supply of nutrients, water and root state, resulting in growth and increased productivity than traditional farming on the land. In regions with little arable land or water supply, soilless culture is of special importance, and is commonly practiced in controlled settings, such as greenhouses and vertical farming systems. The two main categories of soilless systems include hydroponics (growing plants in nutrient solution e.g. NFT, DWC, aeroponics) and substrate-based (root anchoring in an inert material). The main benefit is the high level of water conservation and minimization of soil-borne diseases. Nevertheless, the soilless cultivation is costly to install at the beginning and needs skilled workers to maintain constant checks on nutrient solutions. Considering these features, it is the critical technological base of modern vertical farming systems and plant factories, which is the subject of this review.

2.1. Soilless Cultivation Systems

Modern vertical farming heavily relies on soilless cultivation systems that provide optimal control over plant growth conditions. Among these systems, hydroponics, aeroponics, and aquaponics are the most widely adopted due to their high efficiency, water conservation, and suitability for urban agriculture (Despommier, 2010; Benke & Tomkins, 2017).

2.1.1. Hydroponics

Hydroponics is a system in which plants grow in a nutrient-rich water solution instead of soil. This method allows precise control over nutrient composition, pH, and electrical conductivity, resulting in faster growth and higher yields compared to traditional cultivation. Hydroponic systems use up to 90% less water than conventional farming and can be implemented in limited spaces, such as greenhouses or vertical farms (Table 1, Figure 1A) (Harris, 1992; Resh, 2022).

2.1.2. Aeroponics

Aeroponics represents a further advancement, where plant roots are suspended in the air and periodically sprayed with a fine mist containing water and nutrients. Because the roots receive abundant oxygen, this technique enhances nutrient absorption and accelerates growth. It also minimizes water use and eliminates the need for growth media, making it a sustainable solution for future urban agriculture (Table 1 , Figure 1B) (Munoz and Joseph, 2010; Al-Kodmany, 2018).

2.1.3. Aquaponics

Aquaponics on the other hand, integrates hydroponics with aquaculture the farming of fish or aquatic organisms. In this symbiotic system, fish waste provides nutrients for plants, while plants naturally filter and purify the water that returns to the fish tanks. This closed-loop system conserves water, reduces chemical fertilizer use, and promotes circular food production (Table 1, Figure1C) (Love et al., 2015; Goddek et al., 2019).

These systems collectively contribute to the sustainability and efficiency of vertical farming by maximizing resource use, minimizing waste, and ensuring year-round production under controlled environmental conditions (Kalantari et al., 2017a).

Table 1. Transition from Soilless Cultivation to Vertical Farming Systems.

Cultivation system	Key Characteristics	Major Benefits	Common/Applicable Technologies
Hydroponics	A soilless farming system where plants grow in nutrient-enriched water instead of soil.	Ensures faster and more uniform plant growth; prevents soil-borne diseases and pests; reduces the need for fertilizers and pesticides.	Environmental monitoring systems; automated irrigation controllers; LED grow lights; renewable energy devices (solar, wind, geothermal); vertical racks and conveyor belts; remote-control farming software; nutrient dosing units; climate control and HVAC systems; and agricultural robots.
Aeroponics	An advanced type of hydroponics that fertigates plants by spraying the roots with a fine mist of water and nutrients.	Saves up to 90% more water compared to conventional farming; allows better root oxygenation; enables cleaner and more sustainable crop production.	Precision misting systems; humidity and nutrient sensors; programmable lighting units; data-based growth monitoring tools; renewable power technologies; and automated climate control systems
Aquaponics	Integrates fish farming (aquaculture) with hydroponic plant cultivation, forming a closed, self-sustaining ecosystem.	Promotes a natural nutrient cycle: fish waste becomes plant fertilizer, and plants purify the water for the fish; produces both food and plants efficiently.	Closed-loop water circulation systems; biofilters; aquaculture tanks; renewable energy solutions; programmable control systems; rainwater harvesting units; and automated feeding and monitoring robots.

2. General Function of a Vertical Farming System

The general function of a vertical farming system can be illustrated schematically. This schematic represents the equipment and conditions required for successful cultivation in a controlled environment, such as a greenhouse or a plant factory. Key components of these systems include insulated walls for energy conservation, an air circulation system, and a dehumidification system that allows for water recycling and reuse. Cultivation trays are arranged on the floors of each level, while artificial lighting is provided both from above the plants and on each floor, one of the most critical pieces of equipment. Additionally, climate control systems regulate temperature and humidity, and tanks supply carbon dioxide and nutrient solutions as needed. Together, these components create a stable and predictable environment that enables uniform plant growth and high-quality production throughout the year (Figure 2) (Vatistas et al., 2022).

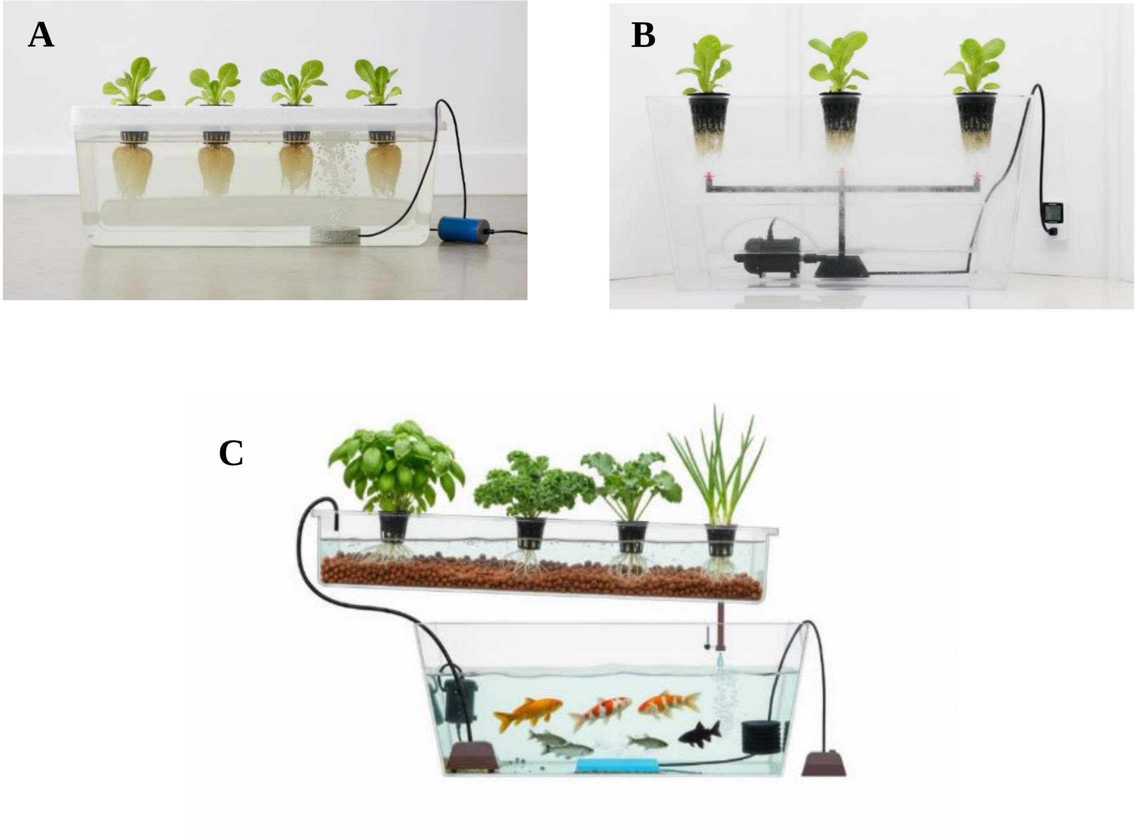

Figure 1. Soilless cultivation systems: Hydroponics (A), Aeroponics (B), and Aquaponics (C).

Fig 2. General view of a vertical farming system.

4. Benefits of Vertical Farming

4.1. Water Savings

Vertical farming significantly reduces water consumption; these methods have been reported to cut water use by up to 90–95% compared to conventional soil-based farming. (Graamans et al., 2018; Al-Chalabi, 2015; Johnson, 2023). These systems enable precise irrigation and nutrient delivery, supplying only the water required for plant growth and thereby avoiding unnecessary waste (Pattison et al., 2018). Moreover, many vertical farms adopt closed-loop irrigation systems that recycle water and nutrients, further enhancing resource efficiency and minimizing overall consumption (Gertphol et al., 2018). As a result, vertical farming emerges as a highly effective solution for regions facing water scarcity or poor-quality water resources (Casey et al., 2022).

4.2. Reduced Land Footprint

Vertical farming reduces the land area required for crop production by stacking plants vertically, which increases yields per unit area. This approach is particularly advantageous in urban areas where agricultural land is scarce (Chen et al., 2020; Barbosa et al., 2015). Controlled-environment techniques decouple production from local climate and soil conditions, allowing continuous year-round cultivation (Van Gerrewey et al., 2022). By producing more food on less land, vertical farming provides a sustainable solution for cities facing land scarcity while ensuring a reliable supply of fresh produce (Carotti et al., 2023; Kulak et al., 2013).

4.3. Environmental Sustainability

Vertical farming offers a more sustainable approach to agriculture by tackling key environmental challenges such as water scarcity, soil degradation, and pollution. Utilizing closed-loop hydroponic systems, these farms drastically reduce water usage and prevent nutrient runoff, which helps protect groundwater quality (Wildeman, 2020; Gruda, 2019; Bol et al., 2018). Controlled environments also optimize energy use and minimize pesticide application, in contrast to conventional open-field farming (United Nations, 2017). By producing food closer to urban centers, vertical farms cut transportation distances, thereby reducing greenhouse gas emissions associated with distribution (Astee and Kishnani, 2010; Kalantari et al., 2017 (a); Chaudhry et al., 2019). Additionally, because vertical farming requires less land, it alleviates pressure on forests and pastures, giving natural ecosystems a chance to recover (Corvalan et al., 2005; Despommier, 2010; Muller et al., 2017; Hallikainen, 2018). Incorporating renewable energy, such as solar or wind power, further lowers carbon emissions and strengthens the environmental benefits of these systems (Tuomisto, 2019; Kikuchi et al., 2018; Xydis et al., 2021; Asgari et al., 2024).

4.4. Use of Advanced Technologies

Vertical farming provides a platform for integrating modern agricultural technologies that enhance productivity and efficiency. Soilless systems, artificial lighting, precise climate control, and the use of beneficial microorganisms like PGPRs allow for faster growth, higher yields, and reduced reliance on chemical fertilizers (Azizoglu et al., 2021). Crops can also be adapted for vertical growth, with traits such as compact size and shorter growth cycles, making them ideal for stacked farming. Furthermore, the integration of smart tools, including artificial intelligence and automated greenhouse management, streamlines operations and maximizes resource efficiency, positioning vertical farming as a forward-looking solution for sustainable urban agriculture (Kusuma et al., 2020).

4.5. Ensuring Food Security

Vertical farming offers a reliable approach to enhance food security by enabling year-round production of fresh crops in controlled environments such as greenhouses. This reduces reliance on seasonal harvests and imported foods (Smith, 2017; Goodman and Miner, 2019). It is particularly effective in urban areas where arable land is limited and transportation costs are high. By regulating environmental factors such as light, temperature, and humidity, vertical farming ensures consistent cultivation of high-quality crops throughout the year, independent of weather conditions (Lee et al., 2023; Tolentino et al., 2023). Greater access to fresh, healthy, and low-pollution produce in cities also strengthens consumer confidence, contributing to improved urban food security (Kim et al., 2015).

4.6. Economic Benefits

Beyond sustainability, vertical farming presents significant economic opportunities. The establishment and expansion of vertical farming industries can create employment in agriculture, technology, marketing, and logistics, boosting local economies (Mukherji and Morales, 2010; Al-Kodmany, 2018; Allegaert, 2020). With high yields per unit area, vertical farms can surpass traditional and conventional greenhouse production, while continuous year-round operations reduce vulnerability to climate fluctuations (Benke and Tomkins, 2017; Katz and Bradley, 2013). Locating farms near urban consumption centers further lowers transportation and storage costs, providing fresher produce and reducing price volatility (Beacham et al., 2019; Healy and Rosenberg, 2013). Vertical farming is also suitable for densely populated regions or areas with harsh climates, offering a sustainable economic model that ensures both productivity and financial stability (Pinstrup-Andersen, 2018; Touliatos et al., 2016).

5. Limitations

Vertical farms have several limitations, including high energy consumption, operational complexity, large capital investment, dependence on external climate, and limited crop diversity and scalability (Table 2)

Table 2. Challenges and Limitations of Vertical Farming

Challenge	Description	References
1. Dependence on External Climate	Crop growth may be influenced even when under controlled systems by the ambient temperature and natural light. Additional light is common, and white LEDs added to deep red (~660 nm) and far-red (~730 nm) increase the growth of leaves and biomass yield in leafy vegetables.	Wildeman, 2020; Farhangi et al., 2025a
2. Operational Complexity	It takes professional human intervention to regulate the lighting, feeding, temperature, humidity, pH and air movement. Automation and sensors reduce the tedious work and mistakes.	Graamans et al., 2018; Kozai et al., 2016
3. Energy Consumption	Artificial lighting, climatization, and pumping consume a lot of energy. A kg of crops can take up to 38.8 kgWh of power in VFs compared to approximately 5.4 kgWh of power in greenhouses. Specific light spectra (red, blue, far-red) enhance the use of light.	Kozai and Toyoki, 2019; Dziumla et al., 2025; Dou and Niu, 2020; Farhangi et al., 2025a
4. High Initial Investment	In terms of investment, construction will be capital-involved as well, multi-layer racks, hydro-/aero-ponics, LED lamps, HVAC system, sensors and automations will be needed. Cost-reduction can also be achieved through LED lights and efficient heating, ventilation and cooling.	Kozai et al., 2015; Farhangi et al., 2025a
5. Limited Crop Diversity and Scalability	The staple crops (grains, root vegetables) are mainly leafy greens, herbs, and some fruits that are not easy to produce at large-scale. Scale causes increased energy, water and operation requirements that render the process economically infeasible.	Pennisi et al., 2025; Aborujilah, 2025; Wang, 2021

6. Vertical Farming and Related Techniques

6.1. Main Components of Vertical Farming

Vertical farming relies on several critical components to create an environment that supports optimal plant growth and maximizes productivity. These components work together to ensure precise control over all growth factors, enabling efficient, year-round cultivation.

6.1.1. Artificial Lighting

One of the most essential components is artificial lighting, typically provided by energy-efficient LEDs. These lights can be tailored to emit specific wavelengths that promote photosynthesis, flowering, and vegetative growth. Unlike natural sunlight, LED systems allow continuous control of light intensity and duration, which is crucial for consistent production throughout the year and for crops that require specific photoperiods (Kozai et al., 2016).

6.1.2. Irrigation and Nutrient Delivery Systems

Controlled-environment agriculture now relies on modern soilless cultivation methods as tools to offer scalable and flexible solutions to urban and high-density farming (Graamans et al., 2018; Resh, 2022; Al-Chalabi, 2015). These systems enable the growers to effectively manage the nutrient delivery process, pH and electrical conductivity to achieve optimal plant growth conditions with minimal wastage of resources. Most systems are closed loop systems to recycle water as well as nutrients, which not only enhances efficiency but also reduces environmental effects caused by conventional soil based agricultural methods, including nutrient runoff and groundwater contamination. These techniques are important elements of the present-day sustainable agriculture strategies as they assist in sustainable production, water scarcity issues, and improving productivity per unit area.

6.1.3. Growth Substrates

Depending on the specific system, plants can be cultivated either in inert substrates such as rockwool, coconut coir, or perlite, or directly in nutrient solutions without any solid medium. These substrates play a crucial role by providing mechanical support to the root system while maintaining a balance between moisture retention and aeration. Proper substrate selection is essential, as it directly affects root health, nutrient absorption efficiency, and overall plant growth and productivity. Factors such as water-holding capacity, porosity, pH stability, and reusability also determine the suitability of a substrate for controlled-environment production systems (Benke and Tomkins, 2017).

6.1.4. Climate Control Systems

Advanced vertical farms employ sophisticated climate control systems to regulate temperature, humidity, and CO_2 concentration precisely. Maintaining optimal environmental parameters minimizes plant stress and promotes faster growth, improved photosynthetic efficiency, and higher yields. Integrated networks of automated sensors and controllers enable real-time monitoring and dynamic adjustments, ensuring stable and energy-efficient operation (Banerjee and Adenaeuer, 2014).

6.1.5. Automation and Monitoring

State-of-the-art vertical farming systems integrate smart automation technologies such as artificial intelligence, driven monitoring, automated irrigation, and precision nutrient delivery systems. These innovations reduce labor dependency, minimize human errors, and enhance consistency in crop management. Real-time data collection and adaptive control further optimize environmental conditions, contributing to greater productivity, sustainability, and system efficiency (Kusuma et al., 2020).

7. Vertical Farming in Greenhouses

Modern vertical farming systems within greenhouses utilize a wide range of advanced technologies to optimize productivity, resource use, and crop quality. These systems integrate innovations such as automated climate control, LED-based artificial lighting, sensor-driven nutrient delivery, and real-time data monitoring. Such technological integration allows growers to maintain ideal environmental conditions for plant growth, minimize resource wastage, and achieve consistent, high-quality yields throughout the year. As a result, vertical farming in greenhouses represents a highly efficient and sustainable model of food production, bridging the gap between agriculture and cutting-edge engineering (Kalantari et al., 2017b).

7.1. Light distribution, shading, and photonic limitations

One of the primary structural challenges in vertical greenhouses is non-uniform light distribution. In a vertical stack, upper tiers or racks closer to light sources (natural sunlight or supplemental lighting) receive more light, while lower tiers, inner shelves, or those on the “shadow side” of racks remain under-illuminated. This gradient in light intensity leads to spatial heterogeneity in photosynthetically active radiation (PAR), which results in variable growth rates, uneven plant size or quality, and inconsistent yield across different layers a major disadvantage when aiming for commercially uniform products (Panotra et al., 2024). Moreover, reliance on natural light in a vertically stacked greenhouse often fails to deliver adequate illumination to all tiers because greenhouse design (roof slope, glazing, spacing) is typically optimized for horizontal cultivation. Without structural modifications to improve light penetration (for example, use of diffusive glazing, reflective surfaces, or light guides), lower layers remain light-limited. Structural shading from racks, beams, or adjoining tiers further exacerbates the problem. Designers of vertical greenhouses therefore face a trade-off: adding more layers increases production area but worsens light uniformity, potentially reducing the per-area yield or quality (Stanghellini and Katzin, 2024). To mitigate lighting limitations, some vertical farms adopt supplemental artificial lighting (e.g., LED). Yet this introduces additional challenges: energy demand rises significantly, and heat generated by lamps may disturb microclimate, especially in lower, denser layers. Indeed, studies show that energy consumption in vertical farming systems may be significantly higher than in traditional greenhouses (Stanghellini and Katzin, 2024). he high energy demand for lighting and climate control remains one of the main barriers to economic and environmental sustainability (Pennisi et al., 2025).

7.2. Microclimate heterogeneity: temperature, humidity, CO_2, ventilation

Beyond light, vertical greenhouses introduce microclimate heterogeneity: because of the stacked layers, airflow, temperature, humidity and CO_2 distribution can become uneven across the different strata. Structural racks and layers may obstruct air circulation, creating zones with poorer ventilation, higher humidity, or stagnation of gases. Such heterogeneity can lead to suboptimal growth conditions, stress on plants, and increased risk of disease or pests in zones where ventilation or microclimate control is insufficient (Vatistas et al., 2022). Maintaining uniform environmental conditions across layers thus requires more complex climate control systems including zoned ventilation/fans, possibly separate sensors for different vertical zones, and possibly active control of air flow and CO_2. These complexities raise both capital and operational costs, and increase the risk of management errors (Vatistas et al., 2022).

7.3. Trade-offs in structural design: glazing, orientation, layering density, maintenance

Design parameters such as greenhouse glazing/translucency, roof shape and orientation, rack spacing, shelf height, and internal layout become more critical in vertical greenhouses than in conventional horizontal greenhouses. A design optimized for horizontal benches might fail when plants are stacked vertically. For instance, glazing that suffices to supply light to a single layer may be inadequate for multiple tiers. Similarly, rack spacing that maximizes area per floor may reduce headroom and airflow, hamper maintenance or harvesting, and exacerbate shading. If the greenhouse uses opaque or partially translucent materials (or shading for temperature control), this further limits natural light penetration forcing more dependence on artificial lighting and increasing energy demand. Therefore, the structural design must balance vertical stacking density with light and microclimate requirements, accessibility for maintenance/harvest, and long-term plant performance (Stanghellini and Katzin, 2024).

7.4. Energy, resource use, and economic/environmental trade-offs

Because of the lighting and climate control requirements, vertical farming systems (especially controlled-environment indoor farms) often exhibit high energy consumption per unit of yield (Stanghellini and Katzin, 2024). While water and nutrient use efficiency may be high (especially in hydroponic or aeroponic systems) and land use efficiency is often better than traditional agriculture, the energy costs and associated greenhouse gas emissions can offset environmental benefits, especially where energy comes from non-renewable sources (Pennisi et al., 2025). Moreover, the increased complexity of structural design, environmental control, maintenance, and automated systems (lighting, ventilation, climate control) increases capital expenditure and operational costs. This makes vertical greenhouses less economically viable for staple or high-biomass crops, particularly when yields or market prices are not high enough to compensate for high costs. Many analyses conclude that vertical farming remains economically feasible mainly for high-value, fast-growing leafy crops (e.g. lettuce, herbs, microgreens), rather than staple grains or root crops (Panotra et al., 2024).

8. Vertical-farming vs greenhouse

Although a vertical farm (VF) and a greenhouse (GH) share the common denominator of Controlled-Environment Agriculture (CEA), they differ greatly in terms of resource utilization, complexity of operations, and suitability to crop production. Vertical farms have the benefit of providing specific control in temperature, humidity, CO 2 and lighting, allowing crops with high value to be year-round and grown faster including leafy greens, herbs and microgreens. Nevertheless, the use of artificial lighting and full climate control also leads to a higher energy consumption and operating expenses, which may offset the positive effects of the environment in case of the use of non-renewable sources of energy (Stanghellini and Katzin, 2024). Conversely, the contemporary greenhouses incorporate a combination of natural sunlight and additional lightings that save on energy use and still attain high productivity in the large biomass crops. The capital and operating expenses tend to be lower in greenhouses than in indoor vertical farms and the simpler nature of the greenhouse construction makes it easier to maintain and scale to higher levels with staple crops. The land-use efficiency, the consumption of energy, and the type of crop are trade-offs between VFs and GHs. Diffuse lighting, reflective surfaces, zoned climate control and modular vertical racks are some of the strategies that can be used to optimize the microclimate conditions and productivity in both systems. A combination of the advantages of greenhouse design and vertical farming methods would be able to improve the sustainability, mitigate the environmental impact, and increase economic viability (Table 3) (Vatistas et al., 2022; Pensis et al., 2025).

Table 3. Comparison between Vertical Farms (VFs) and Greenhouses (GHs)

Criterion	Vertical Farms (VFs)	Greenhouses (GHs)
1. Light Source	100% artificial (LEDs, custom spectra) lighting.	Blending of natural daylight + artificial lighting
2. Climate Control	Complete temperature, humidity, CO2 control; very automated.	Partial control; takes advantage of the ambient climate + auxiliary systems.
3. Energy Consumption	High (up to ~38.8 kWh/kg produce); it depends on the integration of renewable.	Less (~5.4 kWh/kg average); the sunlight decreases the amount of electricity.
4. Water Use Efficiency	Extremely high (closed-loop hydroponics, up to 90 -95% savings)	High, but less than VF; commonly hydroponic in the case of partial recycling.
5. Crop Types	Fast-growing crops (leafy greens, and herbs, microgreens, etc.) are high-value products.	Greener biomass crops (tomatoes, cucumbers, peppers, staple crops)
6. Capital and Operating Costs	High initial investment (CAPEX and OPEX) LEDs, racks, HVAC, sensors.	Reduced CAPEX and OPEX; reduced construction and maintenance.
7. Land-Use Efficiency	Very high (seven-layered stacking, city integration)	Moderate; horizontal scheme with little vertical overlays
8. Operational Complexity	High (demands skilled staff, computerization, surveillance)	Less expensive; less difficult to maintain.
9. Sustainability Potential	There is a high probability of good with a renewable power source, otherwise there is a high chance of high carbon footprint.	Balanced; reduced energy footprint, low land-use efficiency.
10. Optimization Strategies	Even lighting, reflective floors, zone controlled climate, modular display racks.	Diffuse glazing, optimization of the orientation, additional LEDs.

9. Technological Trends in Vertical Farming

Present-day vertical farming is progressively turning to cutting-edge technologies to improve their crop productivity, resource use, and management precision. The key innovations are the deployment of sensor networks, actuators, artificial intelligence (AI), Internet of Things (IoT), and intelligent system architectures.

9.1. Soil and Environmental Sensors in Vertical Farming

A variety of sensors monitor environmental and crop-related parameters such as temperature, humidity, CO_2 levels, light intensity, nutrient concentration, pH, and soil or growth medium properties. Actuators respond to sensor signals to adjust climate, irrigation, lighting, and nutrient delivery automatically. This integration enables real-time monitoring, precise control of plant growth conditions, and reduced dependence on manual labor (Chuah et al., 2019; Sowmya et al., 2024)

9.2. Artificial Intelligence (AI)

AI-driven algorithms analyze large datasets collected from sensors, historical growth patterns, and plant physiological data to optimize irrigation schedules, nutrient dosing, and light cycles. Machine learning enables early detection of stress, disease, or nutrient deficiencies, allowing proactive interventions that improve yield and crop quality while minimizing resource waste (Padhiary et al., 2025; Pennisi et al., 2025)

9.3. Internet of Things (IoT)

IoT platforms connect sensors, actuators, and control systems, providing continuous remote monitoring and automated adjustments. Data transmission in real time allows rapid response to environmental changes or anomalies, enhancing system efficiency and reducing human error. When combined with AI, IoT systems can predict future conditions and execute corrective measures automatically, supporting sustainable and high-tech urban agriculture (Rafi et al., 2025; Kumar et al., 2025).

9.4. Smart Structural Design

Modern vertical farms employ innovative structural solutions to maximize space efficiency and crop productivity. Modular racks, tower systems, and conveyor-based structures allow multiple layers of crops to grow in limited footprints without compromising access for maintenance or harvest. Adjustable platforms and movable cultivation layers provide flexibility in plant spacing and canopy management, ensuring that each plant receives sufficient light, nutrients, and airflow. Integrated monitoring technologies track growth, environmental conditions, and resource usage in real time, enabling data-driven adjustments. Such designs not only increase yield per unit area but also reduce labor intensity and improve operational scalability. In addition, modular structures facilitate easy expansion, retrofitting, or relocation, which is particularly valuable in urban or high-density settings (Graamans et al., 2018; Al-Kodmany, 2018; Kozai et al., 2015). Structural innovations also consider ergonomics, allowing safe and efficient access for workers, while maintaining stability and load-bearing capacity for densely stacked crops

9.5. Light Management and Microclimate Control

Effective light and climate management is critical in vertical farms to ensure uniform growth and high crop quality. Combining natural sunlight with adjustable LED lighting allows precise control over intensity, photoperiod, and spectral composition, which can be tailored to specific crop requirements. LEDs can target specific wavelengths to influence morphology, flowering, nutritional content, and secondary metabolites, supporting high-value production (Massa et al., 2018; Dou and Niu, 2020)

9.6. Temperature and Humidity Management

Maintaining optimal temperature and humidity is essential for minimizing plant stress and reducing the risk of diseases in vertical greenhouse systems. These greenhouses use an integrated combination of ventilation, heating, cooling, and humidification technologies to stabilize the microclimate throughout the growing area (Graamans et al., 2018). Advanced sensors continuously monitor key parameters such as relative humidity, CO_2 concentration, and temperature, while climate-control software automatically adjusts system functions to maintain ideal conditions tailored to each crop. Effective environmental management not only supports healthy growth and efficient photosynthesis but also lowers the incidence of pathogens by preventing condensation and microclimate fluctuations (Al-Kodmany, 2018)

10. Plant Factory

Plant factories are entirely technological, closed horticultural cultivation systems in stacked layers with tightly regulated environmental and nutritional conditions of growth (Pennisi et al., 2025; De Donno et al., 2025). Besides the lack of land, high rates of urbanization, and growing food production with a low consumption of natural resources, these systems also solve global issues by supporting the year-round high-density cultivation with minimal land utilization (Benke and Tomkins, 2017; Kalantari et al., 2017b). The pilot research systems represented early PF prototypes that demonstrated the effectiveness of the multilayer cultivation when artificially lit, in hydroponic conditions, and under control of nutrients. The technologies of LED and sensor networks and automation in Japan, South Korea, Europe, and the United States make the commercialization of PFs possible, particularly in the last two decades (Benke and Tomkins, 2017; Kalantari et al., 2017b; Aborujilah, 2025). PFs rely on hydroponics, aeroponics and multilayer farming to maximize the use of production space and strictly regulate light, temperature and humidity. This will ensure that quality crops are grown throughout the year with minimal wastage of resources. PFs are more resource efficient, produce year-round and can maintain a close control of the environment at the expense of far more expensive initial investments and energy requirements than the resource-use efficiency of traditional greenhouses and open-field agriculture. Their shortcomings notwithstanding, automation and intelligent environmental control system integration improve scalability, operational effectiveness, and, consequently sustainability, and makes PFs one of the most promising hi-tech solutions to indoor agriculture (Benke and Tomkins, 2017; Kalantari et al., 2017b; Aborujilah, 2025).

10.1. High-Profit Crops and Advanced Technologies

The economic sustainability of PFs should be based on intelligent choice of crops and introduction of new technologies. The best crops to focus on include high-value crops, like leafy greens, microgreens, specialty herbs, edible flowers, and berries, solanaceous vegetables, and medicinal plants because they have short growth cycles, are highly edible, and niche markets (Sowmya et al., 2024). Modern PFs involve automation and robotics, which accomplish various functions in seeding, transplanting, pruning, harvesting and packaging, making them less costly in terms of labor expenses, human errors and more precise (De Donno et al., 2025; Pereira and Gomes, 2025). Robotic arms and autonomous guided vehicles (AGVs) support continuous production operations, which lead to 24-hour production shifts. The IoT networks along with AI and machine learning constantly measure the environmental variables such as temperature, humidity and CO 2, light intensity, nutrient levels, and pH and regulate irrigation, nutrient delivery, airflow and lighting based on the crop developmental stages (Sowmya et al., 2024). Other sophisticated PFs apply the digital twin model, predictive simulation to test the changes in the environment virtually and decide before implementation, increasing decision-making and reducing risk (Nabaei et al., 2025).

10. 2. Environmental Control

PFs are defined by absolute control of the environment, which is one of the main factors of growth, yield, and quality maximization. HVAC systems, humidifiers and dehumidifiers are used to provide the species-specific optimal temperature and humidity, which produces a stable microclimate not dependent on weather in the external environment. The enrichment with CO 2 facilitates photosynthesis and growth rate, and airflow and filtration systems provide the uniform distribution of temperatures and humidity, as well as eliminate the spread of pathogens. Sensor networks are actively used to monitor the environment in real-time, and AI-powered systems automatically regulate the parameters of the surrounding environment to achieve maximum crop productivity (Graamans et al., 2018).

10.3. Lighting, Nutrient, and Water Management

PFs must have artificial lighting especially low-energy consuming LEDs to supplement or replace natural sunlight. Light-emitting diodes in modern devices can be controlled with accuracy of the light intensity and photoperiod as well as the spectral composition, which can be adjusted to the physiological requirements of each crop. As an example, blue light during vegetative periods or red/far-red during reproductive periods can enhance yield, plant structure and secondary metabolite synthesis (Farhangi et al., 2025). PFs are based on hydroponic and aeroponic systems which allow accurate nutrient and water management. Aeroponics increases root oxygenation and nutrient absorption whereas hydroponic systems have a recirculation of nutrient solutions to ensure the maintenance of optimum pH, EC, and nutrient ratios. (Benke and Tomkins, 2017).

10.4. Future Perspectives and Developments

PFs should also be equipped with artificial lighting particularly low consumption energy consuming LEDs to add or substitute natural sunlight. In the modern devices, the intensity of the light emitted by the light-emitting diodes may be regulated precisely both of the light intensity and photoperiod and the spectral composition, which may be adapted to the physiological needs of a specific crop. To take one example, blue light that comes in during vegetative periods, or red/far-red light during reproductive periods, can increase yield, plant structure and secondary metabolite production (Farhangi et al., 2025). PFs rely on hydroponic and aeroponic systems that enable proper management of nutrients and water. Aeroponics enhances root oxygenation and uptake of nutrients and in hydroponic systems, the nutrient solutions recirculate in order to maintain optimum levels of pH, EC, and nutrient ratios. (Benke & Tomkins, 2017).

11. Examples of Applications and Research

The pilot projects and research works conducted in various regions of the world evidenced the efficiency of vertical farming systems in controlled conditions to be practical practice. Combined, these research results confirm the fact that vertical farming is a reliable and environmentally-conscious method of year-round food production, especially in cities or those areas where the amount of arable land is minimal. Multi-tier formats of greenhouse systems have also been successfully used to cultivate leafy vegetables in Europe and Asia, including lettuce (*Lactuca sativa*) and basil (*Ocimum basilicum*), whereby the combination of hydroponic or aeroponic technologies and artificial LED light could be used to ensure year-round production of them (Pérez-Urrestarazu et al., 2017; Al-

Kodmany, 2018). The use of water, nutrient management and space have also been enhanced through innovation of automated environmental control system. The advantage of such controlled-environment systems is to maintain the climatic conditions unchanged, reduce wastage of the resources, and improve the quality of products, which proves the feasibility of vertical farming as the scalable model of the eco-friendly agriculture (Al-Kodmany, 2018). Recent assessments in 20242025 indicate that streamlined LED lighting, intelligent irrigation, and model-based energy management play a huge role in environmental effects reduction and operation cost and also productivity enhancement. These outcomes render vertical farming one of the significant aspects of urban agriculture in the future, which is sustainable (Pinis et al., 2025; De Donno, 2025). Plant factories (PFs) also acquire a significant portion of attention in the global arena because of its wide range of application and the ability to encourage a massive production of numerous crops. One of the examples is a vertical farm made of containers that was developed in Sweden by IKEA and it was found successful when it comes to growing lettuce. The environmental analysis of inter-lighting, and vertical machinery of LED was determined to cause the most considerable environmental impact, but the impact can be significantly diminished by employing renewable energy sources (Martin et al., 2024). PFs are also used in extracting the high-value medicinal and aromatic plants such as basil and oregano to obtain essential oils as well as used as a drug in Europe. It is because the quality of the products remains unchanged, and it can be attributed to the strong control over the environmental conditions to a large extent, which makes PFs particularly suitable with the specialty crops (Pennesi et al., 2025). Similar importance of system design and the possibility of reducing the climate-related and resource-related impact of vertical farms significantly in comparison with traditional greenhouses are also supported by the comparative LCA studies in Finland (Joensuu et al., 2024). Controlled-environment agriculture is an area of pharmaceutical studies that has been conducted in the United States. Anti-inflammatory and anticancer bioactive compound, apigenin, that had been grown vertically could be obtained in higher concentrations in medicinal cultivation of such plants as chamomile (*Matricaria chamomilla*) and parsley (*Petroselinum crispum*) (Dsouza et al., 2024). Overall, the case studies of such practices in the world demonstrate that PFs and vertical farming do not only focus on leafy greens. That they are able to produce homogenous, high value and high quality crops and that they can also be engineered to be energy efficient and sustainable only further reinforces their growing significance to the modern day agricultural industry.

Conclusion

Vertical farming is one of the promising techniques that can be used to improve food security in urban areas and sustainable agricultural practices in terms of rising population density, a limited arable land area, shortage of water and climate change. These systems can produce high productivity and high-quality crops all year round by incorporating modern technologies like LED lighting, automated nutrient delivery, sensors, artificial intelligence, as well as robotics. Although the idea is promising, vertical farming suffers some setbacks such as the high start-up capital, energy usage, and scale of variety of crops. The solution to these obstacles would involve energy-saving technologies and integration of renewable energy, circularity in resource management, and indoor-adapted crop breeding. Besides, urban farmers should be educated and trained, interdisciplinary cooperation among agronomists, engineers, architects, and policymakers should be implemented to make the implementation effective and long-term sustainable. Vertical farming can also help lower food miles and turn cities into greener spaces and create more resiliency to climate-related disruptions when properly planned in the urban context. Through further research, technology advancement and funding, vertical farming is set to be a core part of sustainable urban food systems in the future to help ensure a sustainable environment, climate change resiliency, and better quality of life in urban centers.

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