



# **A Review on Hydroponics and Vertical Farming for Vegetable Cultivation: Innovations and Challenges**

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## **Authors' contributions**

*This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.*

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## ABSTRACT

Hydroponics and vertical farming represent transformative innovations in agriculture that provide sustainable and efficient solutions to the growing demand for fresh and nutritious vegetables around the world. The two modern cultivation techniques produce high yields within limited spaces, making them especially suitable for urban and peri-urban environments. This review delves into the underlying principles, key technologies, and the multifaceted challenges associated with these advanced farming systems. By leveraging controlled-environment agriculture, they optimize water and nutrient use while minimizing the dependency on arable land and traditional farming practices. However, widespread adoption faces hurdle such as substantial initial investment, energy-intensive operations, and the need for specialized technical expertise. This paper mentions some recent breakthroughs such as improved LED lighting, automation, and AI-driven monitoring of these systems that have amplified their efficiency and scalability. It also highlights the environmental and economic benefits and plays a crucial role in developing food security, reducing carbon footprints, and enabling sustainable urban agriculture. By analyzing the pros and cons, this paper will offer valuable insights to researchers, policymakers, as well as practitioners who desire to mainstream hydroponics and vertical farming into other agricultural practices.

*Keywords: Hydroponics; vertical farming; techniques; Urban area; vegetable.*

## 1. INTRODUCTION

Global population growth and urbanization have increased the demand for sustainable food production methods (Al Meselmani, (2024). Conventional agriculture has its limitations, including shrinking arable land, climate variability, and water scarcity Benke, & Tomkins, (2017). Furthermore, traditional farming practices tend to be resource-intensive, as they require large inputs of water, fertilizers, and pesticides, which can be detrimental to the environment in the long run Rajaseger et al., (2023). Aeroponics and hydroponics give year round production and reduce the crop losses. Moreover, the agricultural sector is currently faced with labor shortages, logistical inefficiencies, and the unpredictability of weather patterns due to climate change Magwaza et al., (2020).

Hydroponics gives several advantages but some setbacks must be crossed in its proper use. Main of them includes the cost at the time of its preliminary setting, technicality level, and the large use of energy. Further nutrient management and disease prevention become critical factors to keep optimal crop yield in the system of hydroponic cropping Khatri et al., (2024). This technique holds much promise to overcome numerous drawbacks associated with conventional land-based farming Varun Kumar and Verma, (2024). The ability to grow plants in controlled environments offers invaluable opportunities to increase food productivity, especially in urban contexts where arable land access is limited Sharma et al., (2023).

Hydroponics and vertical farming have recently come into the limelight as the best alternatives for vegetable cultivation in this scenario Reddy et al., (2022). These innovative approaches exploit the technologies to overcome the shortcomings of traditional methods, thus ensuring solutions that maximize land use efficiency and resource optimization Ashok, and Sujitha, (2020). They make use of controlled environments that enable the production of quality vegetables throughout the year regardless of the climatic conditions Khan et al., (2020). Furthermore, their potential to integrate with urban settings presents unique opportunities to reduce the carbon footprint associated with food transportation and distribution, thus contributing to the broader goals of sustainable urban development (Pojani, and Stead, 2015).

With dwindling farmlands and rigorous winters in Kashmir, an excellent alternative appears in the form of vertical farming. The procedure allows growing organic pesticide-free produce in an artificially controlled indoors without chemical additives Resh, (2022). Therefore, by substituting conventional open- field agriculture with closed, indoor vertical systems, it is possible to considerably decrease occupational hazards connected with regular agriculture Mir et al., (2022). This solution should be considered by the agricultural scientists, universities, and research institutions. Under varied climatic conditions and crop types, hydroponic production showed different results Gashgari et al., (2018). Greenhouse vegetable cultivation challenges include standardizing growing solutions to

enhance the quality and quantity of yields, ensure efficient water management, and decrease environmental impact (Schwarz et al., 2008). Significant work on hydroponic lettuce (*Lactuca sativa* L.) cultivation, especially through water culture and nutrient film techniques, shows an increased leaf yield in such systems Majid et al., (2021).

Hydroponics and vertical farming are aligned with the increasing global focus on sustainable development goals, especially those that target zero hunger, responsible consumption and production, and climate action Sousa et al., (2024). With the growing interest in these technologies, it is important to understand their principles, benefits, and challenges to advance their implementation and scalability in both urban and rural settings Akintuyi, (2024).

## 2. PRINCIPLES AND TECHNOLOGIES

### 2.1 Hydroponics

Hydroponics is an advanced, soilless culture technique through which the roots of the plants absorb nutrients from a well-formulated mineral-enriched solution Pradhan, and Deo, (2019). This technology does not depend on soil for cultivation purposes, hence it can provide better-controlled and more efficient growth conditions Khan, et al., (2020). This is highly effective in regions with poor quality of soil or less arable land.

**Cost of Hydroponic Farming for One Cycle, According to krishijagran.com Dec 2022:** Hydroponic farming has a one-month production cycle, for which the following costs arise in one

cycle: It takes ₹15,000 as electricity. Seeds would cost ₹20,000. Fertilizers come for ₹20,000.

Labor charges are ₹10,000. Maintenance of ₹5,000 would be required. Packing and transportation cost ₹10,000. The overall cost for one production cycle is ₹80,000.

**Profit in Hydroponic Farming:** From one crop of lettuce to be grown on a 5,000 square foot area: The total production from the area is 3,200 kg. 1,000 kg is wastage. The net product is 2,200 kg. At the market price of ₹350 per kg, total yield value comes out to be ₹7,70,000. The profit margin will be derived as follows by deducting per-cycle cost from total earning: Profit Margin = ₹7,70,000 - ₹80,000 = ₹6,90,000 in every cycle.

**Hydroponic Farming Investment Per Square Foot:** A total investment of ₹20,00,000 including both initial setup and ongoing costs, has been made to cover an area of 5,000 square feet. Investment per square foot will be ₹400 for the initial investment. The per-cycle investment per square foot is ₹16.

**Hydroponic Farming Profit Per Square Foot:** With a total profit margin of ₹6,90,000 for a 5,000-square-foot area, the profit per square foot per cycle is ₹138.

Hydroponics involves growing plants in a water-based, nutrient-rich solution without using soil. This system also supports continuous crop production by controlling variables like nutrients, pH levels, and water, thereby reducing crop losses due to pests and diseases, and letting plants grow faster and more efficiently. The major hydroponic systems are:



Fig. 1. Image of hydroponics

## 2.2 Nutrient Film Technique (NFT)

In the NFT system, a constant, thin film of nutrient solution flows over plant roots housed in sloped channels Burrage, (1992). This ensures that roots receive a consistent supply of nutrients and oxygen while maintaining access to air for respiration Rossouw, (2015). It is highly efficient but requires careful monitoring to prevent blockages or system failures.

As shown in Fig. 2, nutrients are pumped through tubes or pipes and flow over the plant roots before draining away. In the 1960s, Dr. Alen Cooper developed the Nutrient Film Technique (NFT) system to overcome the limitations of the ebb and flow method. The NFT system continuously circulates water or nutrient solutions through the system and into the growth tray with a water pump without a timer Domingues et al., (2012).

## 2.3 Deep Water Culture (DWC)

Plants in this system are suspended above a reservoir with their roots fully submerged in oxygenated nutrient solutions Chen et al., (2016). Air pumps and diffusers maintain oxygen levels, so the roots do not suffocate. This system is easy to set up and supports fast-growing plants.

In DWC, the roots of the plants are submerged directly into a deep, oxygen-rich reservoir that contains a nutrient solution Gómez et al., (2019). The plants are supported by floating platforms or rafts, while air stones or pumps provide sufficient oxygen levels in the solution. This method is well suited for larger crops such as tomatoes and cucumbers.

## 2.4 Aeroponics

Aeroponics delivers nutrients through a fine mist sprayed directly onto plant roots. The mist ensures thorough aeration and maximizes the surface area exposed to nutrients Min et al., (2023). This method uses minimal water and nutrients but demands high technical precision and maintenance.

Aeroponics is a method where plants are grown with their roots suspended in the air and misted with nutrients, hence eliminating the need for soil Kumar et al., (2024). This method encourages faster growth, reduces water usage, and allows

for more controlled environments, which can help produce crops year-round and reduce losses due to soil-borne diseases or pests Gurley, T. W. (2020).

Aeroponics is a soilless farming technique in which the roots of the plants are suspended in the air and periodically misted with a nutrient-enriched solution Sharma et al., (2018). It ensures better aeration and oxygenation of the roots, thereby promoting faster plant growth. Aeroponic systems can be further subdivided into categories based on the pressure used in the misting process Kumar et al., (2024).

## 2.5 Drip Systems

Nutrients are delivered through a network of drippers placed near the base of the plant, allowing for targeted and adjustable feeding Baras, (2018). These systems are scalable and efficient, making them popular for commercial hydroponic setups Chowdhury et al., (2020).

Drip irrigation is a hydroponic method in which nutrient solutions are supplied directly to the roots of plants through a system of tubes and emitters Pinstrup-Andersen, (2018). This method provides direct control over the timing and amount of nutrient delivery, with less water waste and maximum absorption efficiency.

## 2.6 Wicking Systems

A passive approach that relies on capillary action, wicking systems use absorbent materials to transport nutrients from a reservoir to plant roots Kumar, and Dey, (2024). While simple and cost-effective, they are best suited for smaller-scale or low-maintenance operations.

## 2.7 Aquaponics

Aquaponics is a hybrid system that merges hydroponics with aquaculture, the practice of rearing aquatic animals like fish or shrimp Eigenbrod, and Gruda, (2015). In this setup, waste from the aquatic organisms is transformed into nutrients for the plants, while the plants naturally purify the water, thus creating a mutually beneficial relationship Kumar, et al., (2024).



Fig. 2. Image of hydroponic cultivated vegetable crops

Table 1. Adopted different techniques for water saving in vertical farming

Technique	Description	Water Savings
Drip Irrigation	Precise delivery of water directly to plant roots	Up to 70%
Hydroponic Systems	Recirculating water with dissolved nutrients	Up to 90%
Aeroponic Systems	Misting plant roots with nutrient-rich water	Up to 95%
Moisture Sensors	Monitoring soil moisture levels for optimized irrigation	Up to 40%
Rainwater Harvesting	Collecting and storing rainwater for irrigation	Varies

Source Panotra et al., (2024)

**Table 2. Different type of hydroponic system**

<b>Hydroponic System</b>	<b>Characteristics</b>	<b>Reference</b>
Wick System	The Wick system is a low-cost hydroponic method that absorbs nutrients via capillary action through roots and inert material. It's useful for teaching hydroponics culture in areas with limited power access and educational institutions. However, it's not suitable for sustainable crop production, especially for small farmers.	(Ferrarezi and Testezlaf, 2014; Elkazzaz, 2017)
Deep Water Culture (DWC)	The Deep-Water Culture technique in hydroponics involves suspending plant roots in nutrient-rich water, using an air stone for air supply. Plants are grown in net pots, with oxygen, nutrients, pH, and salinity monitored to prevent mold and algae formation.	(Sharma et al., 2019; Singh et al., 2019)
Nutrient Film Technique (NFT)	The nutrient film technique (NFT) exposes plant roots to nutrient-rich water through horizontal pipes. It's more complicated and expensive than media bed culture but offers low evaporation rate. Channel slope, length, and flow rate must be calculated for optimal water flow, oxygen, and nutrients.	(Somerville and Townsend, 2014; Wongkiew et al., 2017)
Drip Irrigation System	The drip hydroponic system involves placing a water tank below the growing tray, where tubes carry water to plants, thereby conserving runoff water and ensuring optimal water distribution.	(Dubey and Nain, 2020)
Aeroponics	Aeroponics is a hydroponic system that uses misting to deliver nutrient-rich water to plants' roots, allowing them to absorb oxygen and nutrients. It's efficient but requires high maintenance to prevent stagnant water and overcrowding. It's not recommended for beginners and can be automated for easier management.	(Santosh and Gaikwad, 2023)
Aquaponics	Aquaponics is a hydroponic technique that mimics a natural ecosystem by using nutrient-rich waste from fish manure, algae, and fish feed in fishponds. Plants act as biofilters, purifying wastewater, which is recycled and released into fishponds, combining plant farming with fish farming.	(Benke, and Tomkins, 2017).
Ebb and Flow (Flood and Drain)	The method involves submerging plants in a nutritional solution in a repetitive manner, and then draining the solution back into a reservoir. The repeated repetition of this cycle enables the supply of nutrients and oxygen to the roots.	(Rajaseger et al., 2023)

Source, Khatri et al., (2024)

**Table 3. Comparing of hydroponic and traditional farming (Reddy et al., 2023)**

<b>Aspect</b>	<b>Hydroponics</b>	<b>Traditional Soil Farming</b>
Water usage	Significantly less, up to 90% less water	More, as water can be lost to soil and evaporation
Space usage	Less space required, suitable for vertical farming	Requires large tracts of land
Location	Can be done anywhere, even in urban settings	Mainly rural locations
Climate control	Year-round farming possible in controlled environments	Dependent on seasonal changes, weather conditions
Soil quality	Not dependent on soil quality	Highly dependent on soil quality and fertility
Pesticide usage	Reduced need for pesticides due to controlled environments	Often requires more pesticides
Growth speed	Faster growth rates due to controlled nutrition	Growth rates depend on various environmental factors
Yield	High yields due to optimized growing conditions	Yield can vary greatly depending on various factors
Startup costs	Higher initial costs for setup and technology	Lower initial costs but might require more long-term investment in soil and pest management
Sustainability	Sustainable; less water and land use	Can be less sustainable due to water, soil, and pesticide usage
Skill required	Requires specific knowledge and training	Traditional farming knowledge often sufficient

Source Khatri et al., (2024)

**Table 4. Advantage and disadvantage of Hydroponics and Aeroponics**

<b>System</b>	<b>Advantages</b>	<b>Disadvantages</b>
Hydroponics	Efficient water and nutrient use High crop yields Precise control over nutrient delivery Suitable for a wide range of crops	Requires specialized knowledge and equipment Dependence on electricity and pumps Risk of waterborne diseases Limited root space
Aeroponics	Minimal water and nutrient use Excellent aeration for roots Reduced risk of plant diseases Faster growth rates	High initial setup costs Requires precise control and monitoring Vulnerable to power outages Limited to certain crop types

Source Panotra et al., (2024)

**Table 5. List of different vertical farms in the words**

<b>S. No.</b>	<b>Name</b>	<b>Location</b>	<b>Products</b>	<b>Technology</b>	<b>Year</b>	<b>Website</b>
1.	The Plant Vertical Farm	Chicago	Artisanal brewery and Mushroom farm	Aquaponics system	2013	<a href="http://www.plantchicago.com">www.plantchicago.com</a>
2.	Sky Greens Farm	Singapore	Leafy green vegetables	Aeroponics system	2009	<a href="http://www.skygreens.appsfly.com/">www.skygreens.appsfly.com/</a>
3.	VertiCrop	Canada	Leafy greens and Strawberries	Fully automated system	2009	<a href="http://www.verticrop.com">www.verticrop.com</a>
4.	Nuvege Plant Factory	Japan	Leafy green vegetables	Automated rack system, LED grow lights	2010	<a href="http://www.nuvege.com">www.nuvege.com</a>
5.	Plantlab VF	Holland	Beans, Corn, Cucumbers, Tomatoes, Strawberries	Advanced LED Aeroponics and Hydroponics	2011	<a href="http://www.plantlab.in">www.plantlab.in</a>
6.	Vertical Harvest	USA	Tomatoes, Lettuce	Recirculating hydroponics	2012	<a href="http://www.verticalharvestjackson.com">www.verticalharvestjackson.com</a>
7.	AeroFarms	Newark	Kale, Greens	LED Lights Recycle water technique	2012	<a href="http://aerofarms.com">http://aerofarms.com</a>
8.	Green Sense Farms	China	Herbs Lettuces	Stacking vertical towers	2014	<a href="http://www.greensensefarmss.com">www.greensensefarmss.com</a>

Source, Mir et al., (2022)

**Table 6. List of different vertical farm in India**

<b>S. No.</b>	<b>Name</b>	<b>Location</b>	<b>Year</b>	<b>Products</b>	<b>Website</b>
1.	Growing Greens	Bangalore, Karnataka	2012	Mint, Spinach and Coriander	<a href="http://growinggreens.in">http://growinggreens.in</a>
2.	Homecrop	Hyderabad, Telangana	2017	Coco peat and composting kits	<a href="http://homecrop.in">http://homecrop.in</a>
3.	Pindfresh	Nayagaon, Punjab	2016	Clay balls, grow bags and net pots	<a href="http://www.pindfresh.com">http://www.pindfresh.com</a>
4.	Urban Kisan	Vishakhapatnam, A. P	2017	Lettuce and hydroponic system	<a href="http://www.urbankisaan.com/about">http://www.urbankisaan.com/about</a>
5.	Sure Grow	Coimbatore, T. N	2017	Lettuce and strawberry	<a href="http://www.suregrow.in/about">http://www.suregrow.in/about</a>
6.	The Living Greens	Jaipur, Rajasthan	2013	Organic input kits and fruit bags	<a href="http://thelivinggreens.com">http://thelivinggreens.com</a>
7.	City Greens	Bangalore, Karnataka	2017	Growing media and seed starters	<a href="http://www.citygreens.in">http://www.citygreens.in</a>
8.	Ikheti	Mumbai, Maharashtra	2011	Seeds and gardening tools	<a href="http://www.ikheti.co.in">http://www.ikheti.co.in</a>

Source, Mir et al., (2022)





**Fig. 3. Image of aeroponics**

### 3. VERTICAL FARMING

Vertical farming is an innovative way in which crops are farmed in vertically stacked layers within controlled environments, maximizing the use of space it occupies Vastitas et al., (2022). It's much more valuable in an urban setting where land may not be readily available (Linn, 2024). They are often combined with either hydroponics or aeroponics to reach higher output with minimal resources used for the crop AIShrouf, (2017).

Vertical farming provides a transformative solution to the challenges of traditional agriculture by redefining how crops are cultivated Kalantari et al., (2018). Utilizing advanced technologies and controlled environments, this method allows crops to be grown in vertically stacked layers within enclosed structures, maximizing land and resource efficiency Panotra et al., (2024). Vertical farming not only enhances crop yields but also minimizes environmental impacts, including reduced water usage, lower pesticide application, and decreased carbon emissions Touliatos et al., (2016). Over recent years, the concept has garnered widespread interest, leading to the establishment of various pilot projects and commercial operations globally Maurya et al., (2024). From compact urban setups to expansive industrial-scale facilities, vertical farming showcases its potential to bolster food security, promote urban sustainability, and support the creation of resilient food systems Agrilyst. (2017).

The cost of vertical farming in India is closely linked with the above factors. However, the

general estimate goes like this according to times *Times of Agriculture magazine 2023*:

1. **Infrastructure Costs:** These are the structural requirements for the buildings, racks, climate control systems, and irrigation setups. Generally, it varies from ₹10,00,000 to ₹1 crore.
2. **Costs of Technology and Equipments:** Advanced technologies include hydroponics, aeroponics, cooling systems, fertigation equipment, and automation systems in vertical farming. It depends upon the scale of operations from ₹5 lakhs to ₹50 lakhs.
3. **Operating Cost:** The term used to describe running cost for operating a facility, that is labor, electricity, water, nutrient solutions, and seeds or seedlings. These costs lie around ₹2 lakhs to ₹5 lakhs every year.

Vertical farming is an innovative agricultural practice in which space is optimized to make food production in the urban setting possible through advanced technologies Despommier, (2013). As the population increases worldwide and the urbanization rate accelerates, traditional farming is faced with the constraints of less arable land, water shortage, and high transportation cost Al-Kodmany, (2018). This problem is answered by vertical farming, as crops are grown in layers or in structures that can be controlled in their environments to efficiently use resources and space Benke, and Tomkins, (2017). The key enabling technologies are:

### 3.1 LED lighting

Advanced LED lighting systems mimic natural sunlight by offering specific light spectrums that are necessary for photosynthesis Nájera et al., (2023). These lights are energy-efficient and can be adjusted to fit the specific growth stages of crops, ensuring optimal plant development Budavári et al., (2024).

### 3.2 Climate Control Systems

These climate control technologies manage temperature, humidity, airflow, and carbon dioxide concentrations Shao et al., (2021). By creating a stable environment, these systems allow year-round cultivation regardless of external weather conditions, enhancing productivity and crop quality Kaiser, et al., (2024).

### 3.3 Automation and IoT

Automation and Internet of Things (IoT) are an integral part of vertical farming in modern times Kozai, (2018). Parameters like nutrient levels, light intensity, and environmental conditions can be monitored in real-time through sensors and actuators Malabadi et al., (2024). Automation will help ensure consistency and bring down labor costs while ensuring efficient operations.

Hydroponics and vertical farming have redefined agricultural practices with the integration of these principles and technologies Maheshwari, (2021), addressing challenges such as land scarcity and climate change, which also provide sustainable solutions to food production and pave a way for resilient and efficient urban agriculture systems Lwasa, and Dubbeling, (2015).



Fig. 4. Image of vertical farming

Table 7. Comparison of vertical farming and traditional agriculture

Characteristic	Traditional Agriculture	Vertical Farming
Land Use	Extensive	Intensive
Water Consumption	High	Low
Pesticide Use	Common	Minimal
Crop Yield	Moderate	High
Labor Requirement	High	Moderate
Energy Efficiency	Low	High
Weather Dependency	High	Low
Transportation Costs	High	Low
Carbon Footprint	High	Low
Urban Accessibility	Low	High

Source Panotra et al., (2024)

**Table 8. List of crop grown under vertical farming**

Crop Category	Examples
Leafy Greens	Lettuce, Spinach, Kale, Arugula, Swiss Chard
Herbs	Basil, Mint, Cilantro, Parsley, Rosemary
Microgreens	Radish, Broccoli, Sunflower, Pea Shoots, Wheatgrass
Fruiting Crops	Tomatoes, Peppers, Cucumbers, Strawberries, Eggplants
Root Crops	Carrots, Radishes, Beets, Turnips, Potatoes

Source Panotra et al., (2024)

**Table 9. Social and environmental benefit of Vertical farming**

Benefit	Description
Food Security	Increased access to fresh, nutritious produce in urban areas
Local Food Production	Reduced food miles and transportation costs
Job Creation	Employment opportunities in urban agriculture and related sectors
Community Engagement	Involvement of local communities in food production and education
Land Conservation	Reduced pressure on agricultural land and preservation of natural habitats
Water Conservation	Efficient water use and reduced agricultural runoff
Reduced Pesticide Use	Controlled environment minimizing the need for pesticides
Climate change Mitigation	Lower carbon footprint compared to traditional agriculture

Source Panotra et al., (2024)

#### 4. INNOVATIONS IN HYDROPONICS AND VERTICAL FARMING

Current technological developments have transformed the hydroponics and vertical farming systems into more efficient, sustainable, and adaptable technologies to the needs of agriculture today Kabir et al., (2023). These innovations encompass.

##### 4.1 Energy-Efficient LED Lighting

More advanced and now more energy-efficient LED developments even allow for lights that match the specific needs of your plants Benke, and Tomkins, (2017). LEDs can now be tuned to emit specific wavelengths of light, optimizing photosynthesis at different growth phases. They also produce minimum heat, thus reducing cooling demands; this allows them to come even closer to the plants, allowing for maximum space utilization Erekaht et al., (2024).

##### 4.2 Automated Nutrient Delivery Systems

Innovations in automated nutrient management introduced systems that can continuously monitor and make adjustments in real-time Halgamuge et al., (2021). These systems use sensors that track pH levels, electrical conductivity (EC), and nutrient concentrations to ensure that there is optimal nutrient availability without waste Hong et al., (2024).

#### 4.3 Artificial Intelligence (AI) and Machine Learning (ML)

AI and ML have actually become integral to predictive farming models in hydroponics and vertical farming Rathor et al., (2024). AI takes environmental data and predicts crop yield, identifies potential issues relating to nutrient deficiencies or a pest threat, and provides optimization of resource usage, for example, computer vision technology detection of early signs of plant stress and disease, which can bring timely interventions Rajendiran, and Rethnaraj, (2023).

#### 4.4 Integration of Renewable Energy Sources

Renewable energy integration is reducing the carbon footprint of these systems. Solar panels and wind turbines are increasingly used to power vertical farming operations Vatistas et al., (2022). Battery storage systems ensure that energy is available during off-peak hours, making the systems more self-sufficient and sustainable Sahoo, and Timmann, (2023).

#### 5. BENEFITS OF VERTICAL AND HYDROPONICS SYSTEM

Hydroponics and vertical farming systems have many advantages over traditional farming methods:

### 5.1 Resource Efficiency

These systems consume much lesser resources. Hydroponics saves up to 90% of water, as the nutrient solution is recycled Ruffi-Salis et al., (2020). Moreover, controlled environments minimize fertilizer and nutrient wastage.

### 5.2 Space Optimization

These systems make maximum use of the available space vertically Toulaitos et al., (2012). These systems are perfect for cities where land is scarce Taylor et al., (2012). The food produced can be locally consumed, which saves on transportation costs and emissions.

### 5.3 Pesticide-Free Cultivation

In controlled environments, the need for chemical pesticides is virtually eliminated, resulting in cleaner, healthier produce Ragaveena et al., (2021). The absence of pests also reduces crop losses, further enhancing sustainability.

### 5.4 Consistent Yields

Vertical farming and hydroponics operate in controlled environments, ensuring year-round production regardless of external weather conditions Duangpakdee et al., (2024). This consistency is critical for maintaining a stable food supply, especially in regions with unpredictable climates.

Leafy greens and herbs will form the backbone of hydroponic and vertical farming due to shorter growth cycles, compact size, and high yield per

area Ampim et al., (2022). Fruiting vegetables such as tomatoes and cucumbers are more space and care-intensive; they need pruning and pollination and, therefore, are easier to grow in hydroponics but can be managed in vertical farming with good support systems Birkby, (2016). Although these plants do not grow easily using traditional methods, aeroponics and specific substrates are known modifications to grow root vegetables as well. Microgreens are suitable for both systems, as they grow fast and require a small space. Leafy greens and herbs will form the backbone of hydroponic and vertical farming due to shorter growth cycles, compact size, and high yield per area Resh, H. M. (2022). Fruiting vegetables such as tomatoes and cucumbers are more space and care-intensive; they need pruning and pollination and, therefore, are easier to grow in hydroponics but can be managed in vertical farming with good support systems. Although these plants do not grow easily using traditional methods, aeroponics and specific substrates are known modifications to grow root vegetables as well. Microgreens are suitable for both systems, as they grow fast and require a small space Ampim et al., (2022).

## 6. REASON VERTICAL OR HYDROPONIC FRUIT BETTER THAN TRADITIONAL GROWN

From a nutritional perspective, the differences between products grown using hydroponic or vertical farming systems and traditional ones can vary depending on several factors, including the crops, growing conditions, and nutrient management. Here are the key distinctions.

**Table 10. Energy efficiency strategies in vertical farming and hydroponic**

Strategy	Description	Energy Savings
LED Lighting	Energy-efficient lighting with targeted wavelengths	Up to 50%
Renewable Energy Integration	Utilizing solar, wind, or geothermal energy sources	Varies
Insulation and Thermal Mass	Minimizing heat loss and maintaining stable temperatures	Up to 30%
Energy Management Systems	Monitoring and optimizing energy consumption	Up to 20%
Natural Ventilation and Cooling	Utilizing passive cooling techniques and airflow	Up to 15%

Source Panotra et al., (2024)

**Table 11. Economic factors in vertical farming and hydroptic**

Factor	Description
Initial Investment	Infrastructure, equipment, and technology costs
Operating Costs	Labor, energy, water, nutrients, and maintenance expenses
Crop Yield and Revenue	Quantity and quality of crops produced and their market value
Market Demand	Consumer preferences, trends, and willingness to pay
Profitability	Return on investment and break-even point
Scalability	Potential for expansion and replication in different locations
Financing Options	Loans, grants, investors, and crowdfunding opportunities

Source Panotra et al., (2024)

**Table 12. List of Different vegetable grown easily under hydroponic and vertical farming**

Category	Vegetable Examples	Hydroponic Suitability	Vertical Farming Suitability
Leafy Greens	Lettuce (Romaine, Butterhead, Iceberg)	High	High
	Spinach	High	High
	Kale	High	High
	Arugula	High	High
	Swiss Chard	High	High
Herbs	Basil	High	High
	Parsley	High	High
	Mint	High	High
	Cilantro	High	High
	Dill	High	High
Fruiting Vegetables	Tomatoes (Cherry, Beefsteak)	High	Moderate to High
	Bell Peppers	High	Moderate
	Cucumbers	High	Moderate
	Eggplant	Moderate	Moderate
Root Vegetables	Radishes	Moderate	Moderate
	Carrots	Low to Moderate	Low
	Beets	Low to Moderate	Low
Microgreens	Broccoli, Mustard, Radish Shoots	High	High
Other	Strawberries	High	High
	Green Beans	Moderate	Moderate

## 7. HYDROPONIC AND VERTICAL FARMING NUTRIENT SOLUTION AND THEIR MONITORING

This is a specialized application of the principles of plant nutrition. Nutrient deficiency symptoms resemble those seen in traditional soil-based farming Kumar et al., (2024). However, the chemistry of hydroponic solutions and vertical farming differs significantly from soil chemistry in several key ways:

### 7.1 Absence of Cation-Exchange Capacity (CEC)

Unlike soil, hydroponic solutions lack cation-exchange capacity provided by clay particles or

organic matter. This absence, along with the lack of soil pores, causes pH, oxygen levels, and nutrient concentrations to fluctuate much more rapidly in hydroponics compared to soil, Urrestarazu et al., (2023).

### 7.2 Nutrient Imbalance from Selective Absorption

Plants take up nutrients selectively. Such selective uptake might throw the balance of the counterions in the solution off balance Samatya, S. (2006). For example,  $\text{NO}_3^-$ , a nutrient that is highly preferred for protein synthesis in the plant, is usually absorbed quickly. This may result in an excess amount of cations in the solution. This may retard the uptake of other nutrient cations,

**Table 13. Different between Traditional farming and vertical or hydroponic system of crop cultivation in nutritional aspect**

<b>Aspect</b>	<b>Hydroponic/Vertical Farming</b>	<b>Traditional Farming</b>
Nutrient Content	Grown in controlled environments with precise nutrient solutions, ensuring consistent profiles, particularly for micronutrients like vitamins and minerals.	Nutrient content varies with soil quality, weather, and environmental factors; soil-rich crops may contain more minerals like iron or zinc.
Flavor and Phytochemicals	Less intense flavors and fewer secondary metabolites (e.g., antioxidants) due to absence of stress factors; optimized lighting can enhance phytochemical production.	Stress factors (e.g., drought, pests) can lead to more robust flavors and higher concentrations of phytochemicals.
Pesticide Residues	Typically pesticide-free, appealing to health-conscious consumers.	May involve pesticide use, resulting in residues, though generally within legal limits when good practices are followed.
Freshness and Post-Harvest Quality	Produce is grown closer to consumers, minimizing transport and nutrient loss, resulting in fresher produce.	Longer transportation distances often result in nutrient degradation before consumption.
Effect of Soil Microbiota	Absence of soil microbiota, which are thought to influence nutritional quality.	Presence of soil microbiota can enhance nutrient uptake and contribute to more nutritionally diverse crops.

such as  $Mg^{2+}$ , if their concentrations are adequate in the solution. Such interference results in deficiency symptoms.

### 7.3 Precipitation of Nutrients

Some nutrients, for instance, iron may precipitate from the solution under some specific pH levels or in the presence of water contaminants and cannot be absorbed by the plants, Jones (2014). There is often a routine pH adjustment or other buffering requirement, or a chelating agent is added to ensure adequate availability Csog et al., (2011).

### 7.4 Standardization and Maintenance

Unlike soil compositions, hydroponic solutions are standardized but must be monitored regularly. Hydroponic solutions are usually maintained in controlled conditions at a nearly neutral pH of around 6.0 and supplied with oxygen to support healthy root growth Jones (2014). When the plant grows and loses water due to transpiration, it is necessary to refill water levels and adjust the concentration of nutrients to a suitable level Ampim et al., (2022).

### 7.5 Monitoring and Adjustments

The regular measurement of key parameters, such as nitrate ion levels, helps in estimating the proportions and concentration of essential nutrients Pinstrup-Andersen, P. (2018). Thus, this ensures a well-balanced solution for the growth of plants Resh, H. M. (2022). A few examples of standardized nutrient formulations include Hoagland solution, Long Ashton nutrient solution, and Knop solution.

### 7.6 Meeting Nutritional Requirements

Like traditional farming, hydroponic nutrient solutions need to follow Liebig's Law of the Minimum; that is, no single nutrient should limit plant growth Winterborne, J. (2005). While the acceptable concentration ranges for most plants are similar, nutrient levels typically fall between 1,000 and 2,500 ppm. Concentrations below this range cause deficiencies, while above this range can cause toxicity Ampim et al., (2022). Optimal nutrient concentrations for particular varieties of plants are obtained through experience or plant tissue analysis Eigenbrod, C., and Gruda, N. (2015).

## 8. CHALLENGES

Despite their advantages, these systems face several challenges:

### 8.1 High Initial Costs

Hydroponic or vertical farming systems require a lot of investment in infrastructure, equipment, and technology (Al-Kodmany, (2018)). The costs involved include LED lighting systems, climate controls, sensors, and automation technologies that can be a barrier to small-scale or resource-constrained farmers.

### 8.2 Energy Dependence

These systems depend on artificial lighting, climate control systems, and automated processes, which tend to incur a high operational energy cost. This dependence on energy sources is challenging in regions with unreliable power supply or high electricity costs.

### 8.3 Technical Skills

Skilled operators are necessary in managing and maintaining the operation of hydroponics and vertical farming systems. Technical competencies will be in aspects like plant science, nutrient management, and troubleshooting.

The absence of technical capabilities will be a setback in maintaining these systems to achieve optimum performance and sustainability.

### 8.4 Scalability

Expansion in terms of volume for massive demand necessitates considerable investment and logistics. Scaling these systems requires transcending spatial challenges, optimization in resource use, and the sustainability of performance within large configurations.

With these challenges tackled through continued innovation and collaboration, hydroponics and vertical farming are going to transform global agriculture with sustainable solutions for the ever-growing demand for food.

## 9. FUTURE PERSPECTIVES

To overcome the challenges and unlock the full potential of hydroponics and vertical farming, future efforts must focus on innovative approaches and strategic collaborations. Key areas for development include:

### 9.1 Developing Cost-Effective Materials and Systems

The development of cheap and robust materials for building hydroponic and vertical farming systems should be given priority. The innovation in lightweight, recyclable, and modular components will be able to bring down setup and maintenance costs to a great extent. The advancement of low-cost sensor technology and energy-efficient equipment will make the systems accessible to small-scale farmers and entrepreneurs as well.

### 9.2 Improving Integration of Renewable Energy

Future systems should focus on integration with renewable energy sources such as solar panels, wind turbines, and geothermal. Research into energy storage solutions, including advanced batteries and hydrogen fuel cells, ensures a constant energy supply even at low levels of renewable energy generation. Collaboration with energy companies to design hybrid systems balancing renewable and conventional sources of energy would further bring down the cost of operating the system.

**Table 14. Challenges and Limitations of Vertical Farming**

Challenge	Description
High Initial Costs	Significant upfront investment in infrastructure and technology
Energy Requirements	High energy consumption for lighting, climate control, and automation
Skilled Labor	Need for specialized knowledge and technical expertise
Limited Crop Variety	Not all crops are suitable for vertical farming systems
Public Perception	Skepticism and resistance towards unconventional farming methods
Regulatory Frameworks	Lack of clear regulations and standards for vertical farming
Scalability Concerns	Challenges in expanding and replicating vertical farms on a large scale

(Source Panotra et al., 2024)

**Table 15. Future Research Directions in Vertical Farming**

Research Area	Description
Crop Improvement	Genetic engineering and breeding for optimized crops
Automation and Robotics	Development of advanced automation systems and robotics
Artificial Intelligence	Application of AI and machine learning for optimized control and decision-making
Renewable Energy Integration	Exploration of renewable energy sources for vertical farms
Waste Management	Innovative solutions for composting and recycling of organic waste
Economic Analysis	In-depth studies on the economic viability and business models of vertical farms
Social Impact Assessment	Evaluation of the social and community benefits of vertical farming
Policy and Regulations	Development of supportive policies and regulatory frameworks

(Source Panotra et al., 2024)

### 9.3 Public-Private Partnership Promotion for Infrastructure Development

The government and private parties should collaborate in setting up infrastructure that can be conducive to the development of vertical farming and hydroponics. Subsidies, tax exemptions, and grants could stimulate investments in research, infrastructure building, and the deployment of technologies. Public-private partnerships could also push the development of urban farming hubs, with such systems integrated into the planning of cities to facilitate local food production.

Knowledge transfer: For such systems to penetrate a wide spectrum, knowledge should be passed on. Farming communities, entrepreneurs, and other stakeholders can receive the appropriate technical and practical know-how through training and capacity building, workshops, and even certification courses. Education campaigns raise the public's environmental and economic benefit of such systems, thus enticing people at both community and industrial scales to adopt it.

## 10. CONCLUSION

Hydroponics and vertical farming represent highly transformational agricultural approaches in order to address important issues related to land shortages, water deficiencies, and requirements of sustainable food. As a result, such systems show potential promise for their utilization in the context of urbanization and scarce resource utilization for year-round cultivation with zero pesticides.

However, the journey to widespread use will need concerted efforts to overcome current limitations. The high initial costs, energy demands, and technical expertise barriers will need to be overcome through technological innovation, policy support, and collaborative initiatives. Advances in automation, renewable energy integration, and cost-effective designs will continue to push these systems toward broader accessibility and scalability.

The role of supporting government policies coupled with public and private investment to create the enabling environment to facilitate growth cannot be downplayed. As such systems develop, they hold promises of transformation in food production and therefore contribution to food security in the world, as well as sustainable urbanization.

### DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1. Yes used chatGpt for some correction

### COMPETING INTERESTS

Authors have declared that no competing interests exist.

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