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

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

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 scarcityBenke, & 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 runRajasegere*t 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 changeMagwaza*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 scenarioReddy *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 optimizationAshok, and Sujitha, (2020). They make use of controlled environments that enable the production of quality vegetables throughout the year regardless of the climatic conditionsKhan *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 additivesResh, (2022). Therefore, by substituting conventional open- field agriculture with closed, indoor vertical systems, it is possible to considerably decrease occupational hazards connected with regular agricultureMir *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 actionSousa *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 settingsAkintuyi, (2024).

Principles and Technologies

1. Hydroponics

Hydroponics is an advanced, soilless culture technique through which the roots of the plants absorb nutrients from a well-formulated mineral-enriched solutionPradhan, and Deo, (2019).This technology does not depend on soil for cultivation purposes, hence it can provide better-controlled and more efficient growth conditionsKhan, *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.comDec 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:

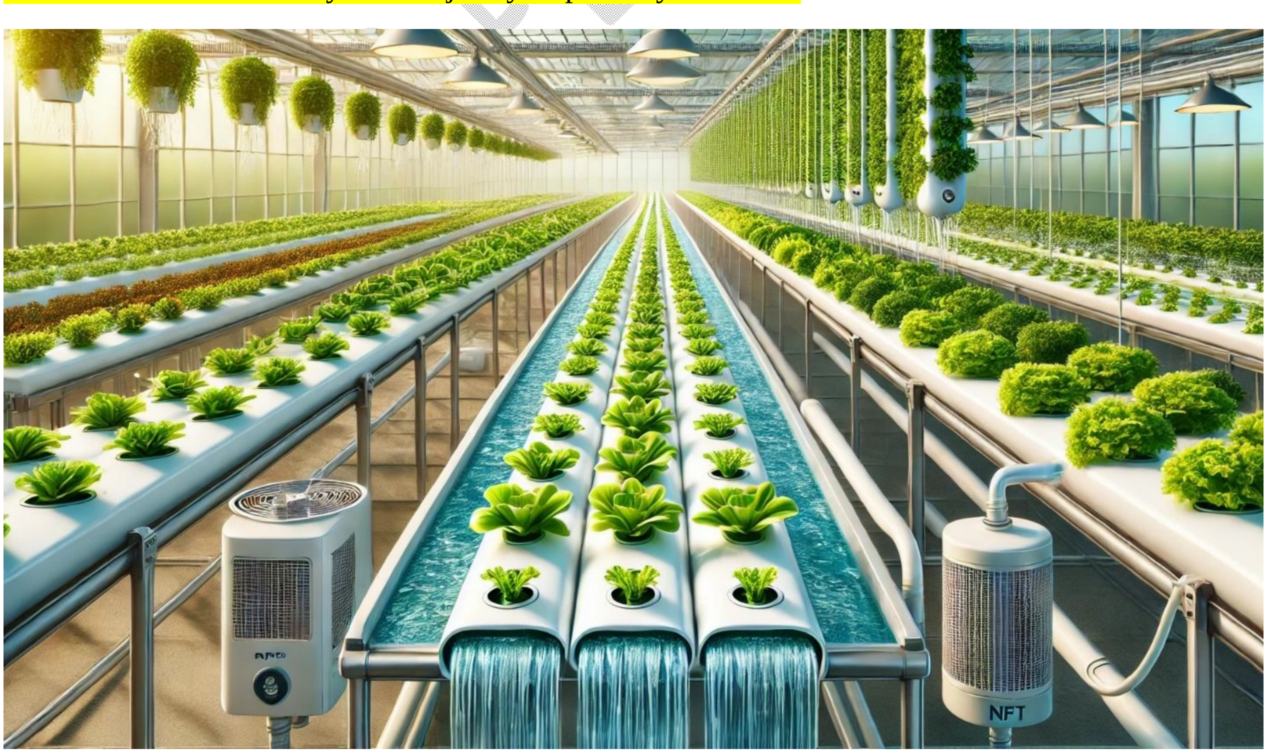

Figure-1. Image of hydroponics

a. Nutrient Film Technique (NFT)

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

As shown in Figure-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).

b. Deep Water Culture (DWC)

Plants in this system are suspended above a reservoir with their roots fully submerged in oxygenated nutrient solutionsChen *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.

c. 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 nutrientsMin*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 soilKumar *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 pestsGurley, 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 processKumar*et al.*,(2024).

Figure-2. Image of hydroponic cultivated vegetable crops

d. Drip Systems

Nutrients are delivered through a network of drippers placed near the base of the plant, allowing for targeted and adjustable feedingBaras, (2018). These systems are scalable and efficient, making them popular for commercial hydroponic setupsChowdhury *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.

Table1.Adopted differentTechniquesfor water saving inVerticalFarming

Technique	Description	WaterSavings
DripIrrigation	Precisedeliveryofwaterdirectlytoplantroots	Upto70%
HydroponicSystems	Recirculatingwaterwithdissolvednutrients	Upto90%
AeroponicSystems	Mistingplantrootswithnutrient-richwater	Upto95%
MoistureSensors	Monitoringsoilmoisturelevelsforoptimizedirrigation	Upto40%
RainwaterHarvesting	Collectingandstoringrainwaterfor irrigation	Varies

Source Panotra*et al.*,(2024)

e. Wicking Systems

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

f).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 relationshipKumar, *et al.*,(2024).

Table2:Different type of hydroponic system

HydroponicSystem	Characteristics	Reference
WickSystem	TheWicksystemisalow-costhydroponicmethodthatabsorbsnutrientsviacapillaryactionthrough roots and inert material. It's useful for teaching hydroponics culture in areas withlimited power access and educational institutions. However, it's not suitable for sustainablecrop production, especially for small farmers.	(FerrareziandTestezlaf,2014 ; Elkazzaz, 2017)
DeepWaterCulture (DWC)	TheDeep-WaterCulturetechniqueinhydroponicsinvolvessuspendingplantrootsinnutrient-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*etal.*,2019;Singh*et al.*, 2019)
NutrientFilmTechnique(NFT)	The nutrient film technique (NFT) exposes plant roots to nutrient-rich water throughhorizontalpipes.It'smorecomplicatedandexpensivethanmediabedculturebutofferslowevaporation rate. Channel slope, length, and flow rate must be calculated for optimal waterflow, oxygen, and nutrients.	(SomervilleandTownsend,2014; Wongkiew et al.,2017)
DripIrrigationSystem	Thedriphydroponicsysteminvolvesplacingawatertankbelowthegrowingtray,wheretubescarrywatertoplants,therebyconservingrunoffwaterandensuringoptimalwaterdistribution.	(DubeyandNain,2020)
Aeroponics	Aeroponicsisahydroponicsystemthatusesmistingtodelivernutrient-richwatertoplants'roots, allowing them to absorb oxygen and nutrients. It's efficient but requires highmaintenance to prevent stagnant water and overcrowding. It's not recommended forbeginners and can be automated for easier management.	(SantoshandGaikwad,2023)
Aquaponics	Aquaponicsisahydroponictechniquethatmimicsanaturalecosystembyusingnutrient-richwaste from fish manure, algae, and fish feed in fishponds. Plants act as biofilters, purifyingwastewater,whichisrecycledandreleasedintofishponds,combining plantfarmingwithfishfarming.	(Benke, and Tomkins, 2017).
Ebb and Flow(FloodandDrain)	The methodinvolves submerging plantsin anutritional solution ina repetitive manner,andthendrainingthesolutionbackintoareservoir.Therepeatedrepetitionofthiscycleenablesthe supply of nutrients and oxygen to the roots.	(Rajaseger*etal.*,2023)

Source,Khatri *et al.*,(2024)

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

Aspect	Hydroponics	TraditionalSoilFarming
Waterusage	Significantlyless,upto90%less water	More,aswatercanbelosttosoiland evaporation
Spaceusage	Lessspacerequired,suitableforverticalfarming	Requireslargetractsofland
Location	Canbedoneanywhere,eveninurbansettings	Mainlyrurallocations
Climatecontrol	Year-roundfarmingpossibleincontrolledenvironments	Dependentonseasonalchanges,weatherconditions
Soilquality	Notdependentonsoilquality	Highlydependentonsoilqualityandfertility
Pesticideusage	Reducedneedforpesticidesduetocontrolledenvironments	Oftenrequiresmore pesticides
Growthspeed	Fastergrowthratesduetocontrollednutrition	Growthratesdependonvariousenvironmentalfactors
Yield	Highyieldsduetooptimizedgrowingconditions	Yieldcanvarygreatlydependingonvariousfactors
Startupcosts	Higherinitialcostsforsetupand technology	Lowerinitialcostsbutmightrequiremorelong-terminvestmentinsoil and pest management
Sustainability	Sustainable;lesswaterandlanduse	Canbelesssustainableduetowater,soil,andpesticideusage

Skillrequired	Requiresspecificknowledgeandtraining	Traditionalfarmingknowledgeoftensufficient

Source Khatri *et al.*,(2024)

Table- 4- Advantage and disadvantage of Hydroponics and Aeropnics

System	Advantages	Disadvantages
Hydroponics	Efficientwaterandnutrientuse Highcropyields Precise controlovernutrient delivery Suitableforawiderangeofcrops	Requiresspecializedknowledgeand equipment Dependenceonelectricityandpumps Riskofwaterbornediseases Limitedrootspace
Aeroponics	Minimalwaterandnutrientuse Excellentaerationforroots Reducedriskofplantdiseases Fastergrowthrates	Highinitialsetupcosts Requiresprecisecontrolandmonitoring Vulnerabletopoweroutages Limitedtocertaincroptypes

Source Panotra*et al.*,(2024)

Figure-3. Image of aeroponics

2. 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 occupiesVatistas*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 cropAlShrouf, (2017).

Vertical farming provides a transformative solution to the challenges of traditional agriculture by redefining how crops are cultivatedKalantari *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 globallyMaurya*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 thisaccording 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.

Table5:List of different vertical farmsin the words

S. No.	Name	Location	Products	Technology	Year	Website
1.	The Plant VerticalFarm	Chicago	Artisanalbreweryand Mushroomfarm	Aquaponics system	2013	www.plantchicago.com
2.	SkyGreensFarm	Singapore	Leafygreenvegetables	Aeroponicssystem	2009	www.skygreens.appsfly.com/
3.	VertiCrop	Canada	Leafygreensand Strawberries	Fullyautomated system	2009	www.verticrop.com
4.	NuvegePlant Factory	Japan	Leafygreenvegetables	Automatedracksystem, LEDgrowlights	2010	www.nuvege.com
5.	PlantlabVF	Holland	Beans, Corn, Cucumbers,Tomatoes , Strawberries	AdvancedLED Aeroponicsan d Hydroponics	2011	www.plantlab.in
6.	VerticalHarvest	USA	Tomotoes, Lettuce	Recirculating hydroponics	2012	www.verticalharvestjackson.com
7.	AeroFarms	Newark	Kale,Greens	LEDLights Recyclewater technique	2012	http://aerofarms.com
8.	GreenSense Farms	China	Herbs Lettuces	Stackingverticaltowers	2014	www.greensensefarmss.com

Source, Mir *et al.*,(2022)

Figure-4. Image of vertical farming

Vertical farming is an innovative agricultural practice in which space is optimized to make food production in the urban setting possible through advanced technologiesDespommier, (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 costAl-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 spaceBenke, and Tomkins, (2017). The key enabling technologies are:

Table6:List of different vertical farm inIndia

S. No.	Name	Location	Year	Products	Website
1.	GrowingGreens	Bangalore,Karnataka	2012	Mint,Spinachand Coriander	http://growinggreens.in
2.	Homecrop	Hyderabad,Telangana	2017	Cocopeatandcompostingkits	http://homecrop.in
3.	Pindfresh	Nayagaon,Punjab	2016	Clayballs, growbagsandnet pots	http://www.pindfresh.com
4.	Urban Kisan	Vishakhapatnam,A.P	2017	Lettuceand hydroponicsystem	http://www.urbankisaan.com/about
5.	Sure Grow	Coimbatore,T.N	2017	Lettuceand strawberry	http://www.suregrow.in/about
6.	TheLiving Greens	Jaipur, Rajasthan	2013	Organicinputkits andfruit bags	http://thelivinggreens.com
7.	CityGreens	Bangalore,Karnataka	2017	Growingmediaandseedstarters	http://www.citygreens.in
8.	Ikheti	Mumbai,Maharashtra	2011	Seedsand gardeningtools	http://www.ikheti.co.in

Source, Mir et al., (2022)

a). LED lighting

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

b). Climate Control Systems

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

c). Automation and IoT

Automation and Internet of Things (IoT) are an integral part of vertical farming in modern timesKozai, (2018). Parameters like nutrient levels, light intensity, and environmental conditions can be monitored in real-time through sensors and actuatorsMalabadi*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 technologiesMaheshwari, (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 systemsLwasa, and Dubbeling, (2015).

Table 7- Comparisonofverticalfarming and traditionalagriculture

Characteristic	TraditionalAgriculture	VerticalFarming
LandUse	Extensive	Intensive
WaterConsumption	High	Low
PesticideUse	Common	Minimal
CropYield	Moderate	High
LaborRequirement	High	Moderate
EnergyEfficiency	Low	High
WeatherDependency	High	Low
TransportationCosts	High	Low
CarbonFootprint	High	Low
UrbanAccessibility	Low	High

Source Panotra*et al.*,(2024)

Table 8- List of crop grown under vertical farming

CropCategory	Examples
LeafyGreens	Lettuce,Spinach,Kale,Arugula,SwissChard
Herbs	Basil,Mint,Cilantro,Parsley,Rosemary
Microgreens	Radish,Broccoli,Sunflower,PeaShoots,Wheatgrass
FruitingCrops	Tomatoes,Peppers,Cucumbers,Strawberries,Eggplants
RootCrops	Carrots,Radishes,Beets,Turnips,Potatoes

Source Panotra*et al.*,(2024)

Table 9- Social and environmental benefit of Vertical farming

Benefit	Description
FoodSecurity	Increasedaccesstofresh,nutritiousproduceinurbanareas
LocalFoodProduction	Reducedfoodmilesandtransportationcosts
JobCreation	Employmentopportunitiesinurbanagricultureandrelatedsectors
CommunityEngagement	Involvementoflocalcommunitiesinfoodproductionandeducation
LandConservation	Reducedpressureonagriculturallandandpreservationofnatural habitats
WaterConservation	Efficientwateruseandreducedagriculturalrunoff
ReducedPesticideUse	Controlledenvironmentminimizingtheneedforpesticides
Climate change Mitigation	Lowercarbonfootprintcomparedtotraditionalagriculture

Source Panotra*et al.*,(2024)

3. 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 todayKabir*et al.*,(2023). These innovations encompass:

a). Energy-Efficient LED Lighting

More advanced and now more energy-efficient LED developments even allow for lights that match the specific needs of your plantsBenke, 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 utilizationErekath*et al.*,(2024).

b). Automated Nutrient Delivery Systems

Innovations in automated nutrient management introduced systems that can continuously monitor and make adjustments in real-timeHalgamuge*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 wasteHong *et al.*,(2024).

c). Artificial Intelligence (AI) and Machine Learning (ML)

AI and ML have actually become integral to predictive farming models in hydroponics and vertical farmingRathor*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 interventionsRajendiran, and Rethnaraj, (2023).

d). 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 operationsVatistas*et al.*,(2022). Battery storage systems ensure that energy is available during off-peak hours, making the systems more self-sufficient and sustainableSahoo, and Timmann, (2023).

4. Benefits of vertical and hydroponics system

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

a). Resource Efficiency

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

b). Space Optimization

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

c). Pesticide-Free Cultivation

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

d.) Consistent Yields

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

Table10.Energyefficiencystrategiesinverticalfarming and hydroponic

Strategy	Description	EnergySavings
LEDLighting	Energy-efficientlightingwithtargetedwavelengths	Upto50%
RenewableEnergy Integration	Utilizingsolar,wind,orgeothermalenergysources	Varies
InsulationandThermal Mass	Minimizingheatlossandmaintainingstable temperatures	Upto30%
EnergyManagement Systems	Monitoringandoptimizingenergyconsumption	Upto20%
NaturalVentilationand Cooling	Utilizingpassivecoolingtechniquesandairflow	Upto15%

Source Panotra*et al.*,(2024)

Table11.Economicfactorsinverticalfarming and hydropic

Factor	Description
InitialInvestment	Infrastructure,equipment,andtechnologycosts
OperatingCosts	Labor,energy,water,nutrients,andmaintenanceexpenses
CropYieldandRevenue	Quantityandqualityofcropsproducedandtheirmarketvalue
MarketDemand	Consumerpreferences,trends,andwillingnesstopay
Profitability	Returnoninvestmentandbreak-evenpoint
Scalability	Potentialforexpansionandreplicationindifferentlocations
FinancingOptions	Loans,grants,investors,andcrowdfundingopportunities

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

Leafy greens and herbs will form the backbone of hydroponic and vertical farming due to shorter growth cycles, compact size, and high yield per areaAmpim*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 systemsBirkby, (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 areaResh, 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 spaceAmpim*et al.*,(2022).

5. 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-13- Different between Traditional farming and vertical or hydroponic system of crop cultivation in nutritional aspect.

Aspect	**Hydroponic/Vertical Farming**	**Traditional Farming**
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.

6. 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 farmingKumar*et al.*, (2024). However, the chemistry of hydroponic solutions and vertical farming differs significantly from soil chemistry in several key ways:

a) .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).

b). Nutrient Imbalance from Selective Absorption

Plants take up nutrients selectively. Such selective uptake might throw the balance of the counterions in the solution off balanceSamatya, S. (2006) . For example, 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, such as Mg^{2+} , if their concentrations are adequate in the solution. Such interference results in deficiency symptoms.

C). 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 availabilityCsog*et al.*, (2011).

d). 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 growthJones (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 levelAmpim*et al.*, (2022).

e).Monitoring and Adjustments

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

f).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 growthWinterborne, 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 toxicityAmpim*et al.*, (2022). Optimal nutrient concentrations for particular varieties of plants are obtained through experience or plant tissue analysisEigenbrod, C., and Gruda, N. (2015).

7. Challenges

Despite their advantages, these systems face several challenges:

a.) 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.

b). 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.

c). 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.

d). 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.

8. 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:

a). 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.

b). 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.

c). 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.

Table14.ChallengesandLimitationsofVerticalFarming

Challenge	Description
HighInitialCosts	Significantupfrontinvestmentininfrastructureandtechnology
EnergyRequirements	Highenergyconsumptionforlighting,climatecontrol,andautomation
SkilledLabor	Needforspecializedknowledgeandtechnicalexpertise
LimitedCropVariety	Notallcropsaresuitableforverticalfarmingsystems
PublicPerception	Skepticismandresistancetowardsunconventionalfarmingmethods
RegulatoryFrameworks	Lackofclearregulationsandstandardsforverticalfarming
ScalabilityConcerns	Challengesinexpandingandreplicatingverticalfarmsonalargescale

(Source Panotra*et al.*, 2024)

Table15.FutureResearchDirectionsinVerticalFarming

ResearchArea	Description
CropImprovement	Geneticengineeringandbreedingforoptimizedcrops
AutomationandRobotics	Developmentofadvancedautomationsystemsandrobotics
ArtificialIntelligence	ApplicationofAIandmachinelearningforoptimizedcontroland decision-making
RenewableEnergy Integration	Explorationofrenewableenergysourcesforverticalfarms
WasteManagement	Innovativesolutionsforcompostingandrecyclingoforganicwaste
EconomicAnalysis	In-depthstudiesontheeconomicviabilityandbusinessmodelsof vertical farms
SocialImpactAssessment	Evaluationofthesocialandcommunitybenefitsofverticalfarming
PolicyandRegulations	Developmentofsupportivepoliciesandregulatoryframeworks

(Source Panotra*et al.*, 2024)

9. 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)

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

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Details of the AI usage are given below:

1. Yes used chatGpt for some correction

2.

3.

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