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HYDROPONICS AND SOILLESS CULTIVATION IN HORTICULTURAL CROPS: CURRENT TRENDS AND FUTURE PERSPECTIVES

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ABSTRACT

Hydroponics and other soilless cultivation systems have emerged as transformative alternatives to conventional soil-based agriculture, particularly in the production of horticultural crops. These systems provide precise control over plant nutrition, water consumption, and climatic conditions, and are driven by factors such as urbanization, soil degradation, climate variability, and rising global food demand. High yields, better quality, and year-round production are made possible by hydroponic methods such as nutrient film technology, deep-water culture, aeroponics, and substrate-based systems. Crop performance is further improved while resource inputs are reduced when modern lighting, automation, and sensor technologies are integrated with controlled environment agriculture (CEA). Hydroponics has been widely used in gardening for ornamentals, berries, herbs, leafy vegetables, fruit vegetables, and certain medicinal plants. There are also issues with high starting costs, energy consumption, technical complexity, and environmental problems linked to substrate disposal, despite notable benefits including improved water efficiency and decreased illness incidence. The importance of soilless production in future food systems is anticipated to be strengthened by new developments in AI-driven management, sustainable substrates, nutrient recycling, and crop types designed for hydroponic systems. Hydroponics and soilless production of horticultural crops are discussed in this study along with their current trends, technological developments, uses, economic implications, and future directions.
Keywords **:** Hydroponics, Soilless cultivation, Controlled environment agriculture, Vertical farming, Nutrient solution management, Substrate media, Automation and IoT, LED lighting, Urban agriculture, Sustainability.

Introduction

Innovative crop production techniques like hydroponics and soilless agriculture use inert substrates or nutrient-enriched aqueous solutions in place of traditional soil. Compared to conventional soil-based agriculture, these methods provide precise control over water, nutrients, and environmental conditions, resulting in increased production and resource efficiency (Resh, 2013). Although Julius von Sachs and Wilhelm Knop conducted the first hydroponic experiments in the 19th century, commercial use of the technology started in the middle of the 20th century with improvements in greenhouse management and fertilizer formulation (Jensen, 1997). Modern fertigation systems, artificial lighting, and controlled environment agriculture (CEA) have all contributed to the development of hydroponics into a highly advanced production technique appropriate for a variety of horticultural crops (Savvas & Gruda, 2018). Global issues including climate change, soil degradation, land scarcity, and rising population-driven food demand are driving the need for alternate farming techniques. Particularly in metropolitan and peri-urban areas, traditional agriculture must contend with diminishing soil fertility, erratic weather patterns, and a scarcity of arable land (FAO, 2011). By permitting year-round production, cutting water consumption by up to 90%, and lowering reliance on fertile soils, hydroponics provides an effective alternative (Beyena, 2019). Additionally, by eliminating soil-borne illnesses and lowering insect load, these systems support more robust and sustainable production methods (Raviv & Lieth, 2008). Hydroponics has become popular in contemporary gardening for high-value crops such ornamentals, tomatoes, strawberries, herbs, and leafy greens. In urban agriculture, such as rooftop farming, vertical farms, and indoor systems that promote local food production and shorter supply-chain lengths, its significance is further increased (Kozai, 2016). Hydroponics and soilless systems are becoming crucial technologies to guarantee future food security and sustainable horticulture growth as cities grow and environmental restrictions worsen (Despommier, 2013; Benke & Tomkins, 2017).

The Basis of Soilless Culture and Hydroponics

Plant Nutrient Absorption Without Soil

In hydroponics, a nutrient-rich aqueous solution that gives plants all the necessary mineral elements for development takes the place of the natural soil matrix. Nutrient absorption happens through direct root contact with the solution in the absence of soil, allowing for exact control over nutrient concentrations and reducing nutrient losses from leaching (Resh, 2022). Ions are absorbed by root systems via passive diffusion, facilitated transport, and active uptake processes, including proton pumps that preserve electrochemical gradients (Satti & Al-Yahyai, 2017). Compared to traditional soil farming, plants in hydroponic systems usually exhibit quicker growth rates and better biomass accumulation because nutrients are instantly accessible (Jones, 2016). Additionally, a cleaner rhizosphere environment lowers disease incidence and increases plant vigour when soil-borne pathogens are absent.

Important Nutrients and the Functions of Temperature, pH, EC, and DO

All 17 important mineral elements, including macronutrients like nitrogen, phosphorus, and potassium and micronutrients like iron, zinc, and manganese, are necessary for hydroponic systems to function at their best (Sonneveld & Voogt, 2009). Because direct root exposure causes deficiencies or toxicities to manifest more quickly in soilless situations, maintaining nutrient balance is essential. Nutrient availability is significantly influenced by the physicochemical characteristics of the nutrient solution. Ion solubility is determined by pH, and most crops function best in the range of 5.5 to 6.5 (Treadwell *et al*., 2011). To prevent osmotic stress, electrical conductivity (EC), an indicator of total dissolved salts, must be kept within crop-specific limits (Sambo *et al*., 2019). Insufficient dissolved oxygen (DO) can lead to root hypoxia, decreased nutrient absorption, and increased susceptibility to infections. DO is necessary for aerobic respiration in roots (Bar-Yosef, 2008). To maximize root metabolism and avoid oxygen decrease linked to warmer water, water temperatures should typically stay between 18 and 24°C (Savvas *et al*., 2013).

Characteristics of Ideal Soilless Substrates

In several hydroponic and substrate-based growing techniques, soilless substrates act as physical support systems. High porosity, excellent aeration, sufficient water-holding capacity, structural stability, and chemical inertness are all desirable characteristics of a substrate (Raviv & Lieth, 2008). The physical and chemical characteristics of common substrates including cocopeat, perlite, rockwool, and vermiculite vary, which affects nutrient dynamics and root growth. According to (Awang *et al*., 2009), growing medium should support the best possible root–oxygen interaction, maintain a steady pH, and prevent breakdown. Environmental concerns are driving advancements in sustainable substrates, such as biodegradable fibbers and materials derived from organic waste (Gruda, 2019).

Table 1 : Key Properties of Common Soilless Substrates

Substrate	Water-Holding Capacity	Aeration	pH Stability	Advantages
Cocopeat	High	Moderate	Good	Renewable, good CEC
Perlite	Low–Moderate	High	Excellent	Lightweight, inert
Rockwool	Moderate	High	Good	Uniform structure, widely used
Vermiculite	High	Moderate	Moderate	Good moisture retention
Expanded Clay Pellets	Low	High	Excellent	Reusable, durable

Hydroponic Systems and Soilless Media

Major Hydroponic Systems

A variety of system designs are included in hydroponic technologies with the goal of maximizing root-zone oxygenation and nutrient delivery. By suspending plant roots in an oxygenated nutrient solution, Deep Water Culture (DWC) encourages quick nutrient absorption and robust root growth (Resh, 2022). For leafy greens in particular, the Nutrient Film Technique (NFT) effectively distributes and aerates nutrients by circulating a thin film of nutrient solution over sloping channels (Sonneveld & Voogt, 2009). Although it necessitates exact environmental control, aeroponics, which supplies nutrients by fine misting, guarantees maximal oxygen exposure to roots and boosts quicker development rates (Barbosa *et al*., 2015). Drip irrigation methods reduce water loss and provide flexibility for a variety of substrates by directly applying fertilizer solution to each plant's root zone (Raviv & Lieth, 2008). In order to minimize stagnation and enable roots to absorb water and nutrients, ebb and flow (also known as flood and drain) systems periodically flood and then drain the growing tray (Savvas *et al*., 2013).

Wick System (Passive, Non-circulating): The wick system is the simplest hydroponic design in which nutrient solution is drawn from a reservoir to the plant root zone by capillary action through an absorbent wick material. This method requires no pumps or timers, making it low-cost and easy to operate for small or hobby applications (Velazquez-Gonzalez *et al.,* 2022). Advantages include its simplicity and minimal maintenance requirements, while limitations include poor oxygenation at roots and unsuitability for larger or high-water-demand crops (Rajaseger *et al.,* 2023). Typical crops: herbs and small leafy greens with low transpiration rates. Management considerations: choose high-wicking materials, monitor solution depletion frequently, and avoid water-sensitive crops (Velazquez-Gonzalez *et al.,* 2022).

Nutrient Film Technique (NFT): In NFT systems a thin, continuously flowing film of nutrient solution runs along a shallow channel past the plant roots, which are supported in small net pots; roots have constant access to nutrients and oxygen from the film and the surrounding air (Velazquez-Gonzalez *et al.,* 2022). NFT is widely used for lettuce and other shallow-rooted vegetables due to its efficient nutrient use and suitability for high-density, vertical, or conveyor-style layouts (Rajaseger *et al.,* 2023). Main challenges include the system's sensitivity to pump failures (which can quickly stress plants) and the need for precise slope and flow controls to prevent channel dry-out or stagnation (Pomoni *et al.,* 2023). Best practices: redundancy in pumping, routine checks of channel slope and flow rate, and limiting use to crops with small root volumes (Velazquez-Gonzalez *et al.,* 2022).

Deep Water Culture (DWC) / Floating Raft: Deep Water Culture systems suspend plant roots in a large volume of oxygenated nutrient solution or on floating rafts above a deep reservoir; aeration (via air stones) supplies oxygen to roots to maintain healthy respiration (Velazquez-Gonzalez *et al.,* 2022). The floating-raft variant is common in commercial leafy-green production, offering stable nutrient environment and ease of automation (Rajaseger *et al.,* 2023). Strengths include low labor and high yields per unit area, while drawbacks include susceptibility to waterborne pathogens and the requirement for consistent oxygenation and temperature control (Pomoni *et al.,* 2023). Management notes: maintain dissolved oxygen, monitor solution temperature, and implement sanitation protocols to limit pathogen outbreak.

Ebb-and-Flow (Flood and Drain): Ebb-and-flow systems periodically flood crop beds (filled with an inert substrate) with nutrient solution and then drain back to the reservoir; this intermittent cycle provides nutrients and permits aeration during the drain phase (Velazquez-Gonzalez *et al.,* 2022). The method is versatile and can be configured for many crop types, providing a balance between nutrient availability and root oxygenation (Rajaseger *et al*., 2023). Limitations include the need for properly sized pumps and timers and greater mechanical complexity compared with passive systems (Pomoni *et al.,* 2023). Operational recommendations: set flood cycles appropriate to crop stage and substrate water-holding capacity, and ensure good drainage to prevent root hypoxia.

Drip Irrigation Systems (Recovery and Non-recovery): Drip hydroponics uses emitters to deliver nutrient solution directly to the root zone in substrate-based beds; systems can be configured as recirculating (recovery) or non-recirculating (run-to-waste) depending on water and nutrient management goals (Velazquez-Gonzalez *et al.,* 2022). Drip systems are adaptable to many fruiting and vine crops (e.g., tomato, pepper) since emitters can be sized and located to match high localized root demands (Pomoni *et al.,* 2023). Advantages include precise irrigation and compatibility with larger plants; disadvantages include emitter clogging, more complex filtration needs, and the requirement for careful EC/pH monitoring in recirculating modes (Rajaseger *et al.,* 2023).

Aeroponics: Aeroponics suspends plant roots in air and supplies nutrients as a fine mist or aerosol, maximizing oxygen availability at the roots and often accelerating growth rates (Velazquez-Gonzalez *et al.,* 2022). Aeroponic systems are highly water-efficient and enable rapid root zone gas exchange, but they are capital-intensive and sensitive to nozzle or misting failures; even short interruptions can rapidly stress plants (Rajaseger *et al.,* 2023). Suitable applications include high-value crops and research/space agriculture where rapid growth and resource efficiency matter. Operational priorities: maintain high reliability in misting hardware, maintain sterile conditions, and monitor droplet size and frequency to ensure nutrient deposition without root flooding.

Substrate (Media) Culture

Substrate culture uses an inert or organic medium (e.g., rockwool, coco coir, perlite) to support plant roots while nutrient solution is delivered via irrigation; the substrate provides mechanical support and variable water retention characteristics to match crop needs (Velazquez-Gonzalez *et al.,* 2022). This approach is widely adopted in greenhouse tomato, cucumber, and ornamental production due to good root zone stability and ease of mechanization. Key management aspects include choosing a substrate with appropriate porosity and water-holding capacity, implementing regular EC/pH management, and handling substrate replacement or disposal responsibly (Pomoni *et al.,* 2023).

Selection of a hydroponic system is driven by crop type, scale, capital and operational budgets, labor and technical capacity, and local constraints such as energy cost and water quality (Pomoni *et al.,* 2023; Velazquez-Gonzalez *et al.,* 2022). Closed/recirculating systems conserve water and nutrients but require robust monitoring and treatment to prevent pathogen spread; open/run-to-waste systems are simpler but less resource-efficient (Rajaseger *et al.,* 2023). Integration with automation, sensors, and controlled-environment technologies (lighting, temperature, CO_2) improves yield and consistency but increases technical complexity and energy requirements (Rajaseger *et al.,* 2023).

Types of Soilless Substrates

In hydroponic and substrate-based systems, plants are physically stabilized by soilless substrates. Inorganic substrates include rockwool, which is prized for its sterility and uniform pore structure; vermiculite, which is renowned for its superior water retention; and perlite, which has a high degree of aeration (Gruda, 2019). Because of their advantageous water-holding capacity, cation-exchange characteristics, and promotion of beneficial microbial activity, organic substrates including cocopeat and peat moss are frequently utilized (Awang *et al*., 2009). Because it is renewable and biodegradable, cocopeat is especially favoured.

Substrate Selection and Sustainability Considerations

Physical characteristics, nutrient-buffering capabilities, durability, affordability, and crop-specific requirements all play a role in choosing the right substrate (Ronga *et al*., 2021). When choosing a substrate, sustainability is becoming more and more important. For example, despite its advantageous agronomic qualities, peat moss extraction is less sustainable since it increases carbon emissions and ecosystem destruction (Barrett *et al*., 2016). On the other hand, eco-friendly substitutes include cocopeat, composted bark, and other renewable materials. Rockwool and other inorganic substrates provide disposal issues, highlighting the necessity of recycling and ethical waste management techniques (Raviv & Lieth, 2008). In general, crop yield, environmental impact, and long-term survival are greatly influenced by the hydroponic system's design and substrate selection. The future of soilless horticulture will revolve around the integration of sustainable, renewable substrates with resource-efficient system designs.

Nutrient Solution Management

For hydroponic and soilless systems to achieve the best possible plant growth, output, and quality, effective nutrition solution management is essential. Efficiency and sustainability are increased when plants get balanced nutrients in a controlled environment through proper formulation, monitoring, and automation.

Standard Nutrient Formulations for Horticultural Crops

In the absence of soil, fertilizer solutions provide all necessary macronutrients and micronutrients for plant development. The Hoagland and Arnon solution, Steiner's universal formulation, and crop-specific formulas created for tomatoes, cucumbers, lettuces, and ornamentals are common hydroponic formulations (Hoagland & Arnon, 1950; Sonneveld & Voogt, 2009). In addition to micronutrients including iron, manganese, zinc, copper, boron, and molybdenum, these formulations usually include specified ratios of nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur (Resh, 2022). While fruiting crops like tomatoes and peppers flourish at greater electrical conductivity (EC) values (2.5–3.5 mS/cm), leafy vegetables like lettuce require lower EC levels (1.2–1.8 mS/cm) (Schwarz *et al*., 2009). Growth stage, climate, substrate properties, and crop requirements all influence nutrient formula modifications. Toxicities, inadequacies, and physiological diseases are avoided by maintaining a balanced nutritional solution (Sambo *et al*., 2019).

Monitoring and Adjustment of pH, EC, and Nutrient Levels

Efficient nutrient absorption depends on maintaining ideal pH and electrical conductivity (EC). For the majority of hydroponic crops, a pH of 5.5 to 6.5 is appropriate since it guarantees that all necessary elements are available (Sonneveld & Voogt, 2009). Variations from this range may result in toxicities or shortages by decreasing the solubility of nutrients. EC is a measure of total dissolved salts and has to be controlled to prevent osmotic stress (Bar-Yosef, 2008). Maintaining nutritional balance is aided by routine monitoring of solution temperature and nutrient content. To ensure healthy root respiration, for example, temperatures between 18 and 22°C enhance root activity and dissolved oxygen (DO) availability (Tzortzakis & Economakis, 2008). Ionic equilibrium is maintained and the buildup of wasted ions is avoided by periodically replacing or replenishing the nutritional solution (Raviv & Lieth, 2008).

Automation, Fertigation Controllers, and Sensor-Based Management

Automation is becoming more and more important in modern hydroponic systems to maximize fertilizer delivery. Based on predetermined criteria including pH, EC, and crop stage, fertigation controllers automate the mixing, dosing, and timing of nutrient administration (Shamshiri *et al*., 2018). These solutions improve accuracy, cut down on work, and decrease human mistake.

Real-time monitoring and dynamic adjustment of nutritional solutions are made possible by sensor-based technologies such as pH, EC, DO, and ion-selective sensors (Benke & Tomkins, 2017). Growers' decision-making is improved by integration with Internet of Things (IoT) technologies, which offer continuous data logging and remote monitoring (Pantazi *et al*., 2016). In order to improve sustainability and resource efficiency, machine learning algorithms are being utilized more and more to forecast patterns of nutrient uptake and optimize fertigation techniques. By drastically reducing water and fertilizer waste, automation and sensor-driven fertigation provide constant crop performance and improve the sustainability of nutrient management.

Controlled Environment Integration

Plant growth, productivity, and quality may be maximized by the exact manipulation of environmental parameters made possible by controlled environment agriculture (CEA). Combining hydroponics with CEA technology enables for year-round production, improves resource efficiency, and lowers insect occurrence.

Role of Greenhouses, Polyhouses, and Vertical Farming

Crops are shielded from harsh weather, pests, and illnesses by semi-closed buildings like greenhouses and polyhouses. High-density hydroponic production is supported by these buildings, which provide controlled light, temperature, and humidity (Castilla, 2013). By stacking many layers of crops, vertical farming further optimizes space, especially in urban settings, minimizing land footprint and food transportation distances (Banerjee & Adenaeuer, 2014). In order to enable extensive production in constrained spaces, vertical farms are frequently combined with hydroponic or aeroponic systems.

LED Lighting Technologies and Light Recipes

In regulated surroundings, especially in indoor and vertical farms, artificial illumination is crucial. LED lighting provides energy-efficient, spectrum-specific illumination, enabling farmers to modify photoperiod, spectral composition, and light intensity (also known as "light recipes") to affect secondary metabolite synthesis, morphology, and flowering (Massa *et al*., 2008). Photosynthesis depends on red and blue spectra, although additional green, far-red, or

UV spectra might improve quality aspects (Bantis *et al.*, 2018). Recipes for optimized light can increase plant growth while consuming less energy.

Climate Control: Temperature, Humidity, Ventilation, and CO_2 Enrichment

Hydroponic performance depends on maintaining ideal climatic conditions. While ventilation guards against excessive heat and encourages air circulation, temperature and humidity have an impact on transpiration and nutrient absorption (Kozai *et al.*, 2016). Photosynthetic efficiency is improved by CO2 enrichment (700–1,000 ppm), especially in fruiting crops like tomatoes and cucumbers (Van Iersel *et al.*, 2016). Real-time monitoring sensors allow for accurate modifications to preserve crop-specific conditions.

IoT and AI Applications in Environmental Monitoring

Recent developments combine cloud computing, IoT devices, and AI algorithms for real-time environmental monitoring and control. While AI analyses patterns to automate climate and fertigation changes, sensors gather information on temperature, humidity, CO_2, light, and nutrient solution parameters (Shamshiri *et al.*, 2018). As a consequence, agricultural output is increased, labour is decreased, and resource use is optimized.

Table 1: Key Environmental Factors and Optimal Ranges for Hydroponic Crops

Parameter	Optimal Range	Impact on Growth
Temperature (°C)	20–26	Influences metabolic rate, flowering, fruit set
Relative Humidity (%)	60–75	Affects transpiration and disease incidence
CO_2 (ppm)	400–1,000	Enhances photosynthesis and biomass
Light (µmol/m²/s)	150–400	Drives photosynthesis, morphology, and yield
Photoperiod (h)	14–18	Regulates flowering and vegetative growth

Application in Horticultural Crops

Modern horticulture relies heavily on hydroponics and soilless growing, which allow for the year-round, high-yield, resource-efficient production of a wide range of crops. These methods are especially useful for controlled environments, restricted land areas, and urban agriculture.

Leafy Vegetables, Fruit Vegetables, and Herbs

In spite of their short growth cycles, high market demand, and tolerance to nutrient-film and floating systems, leafy plants including lettuce, spinach, kale, and arugula are commonly cultivated hydroponically (Resh, 2022). In order to provide the best possible aeration and nutrient delivery, fruit vegetables such as tomatoes, cucumbers, peppers, and eggplants are also frequently grown in substrate-based systems like rockwool or cocopeat (Sonneveld & Voogt, 2009). Hydroponics helps herbs like coriander, basil, and mint grow uniformly, produce more essential oil, and have fewer insect issues (Kozai *et al.*, 2016).

Fruits like Strawberries and Berries in Substrate Culture

A growing number of berries, including blueberries and strawberries, are grown in soilless and hydroponic systems, particularly on raised or vertical substrate beds. Improved fruit size, colour, and sugar content result from these systems' ability to precisely manage the flow of nutrients and water (Gruda, 2019). In temperate countries with off-season demand, substrate-based farming minimizes soil-borne illnesses and permits year-round production in greenhouses or polyhouses (Teixeira da Silva & Dobránszki, 2014).

Ornamental Crops and Cut Flower Production

In order to satisfy market quality criteria for size, colour, and vase life, hydroponic systems are used to grow ornamental plants and cut flowers including roses, chrysanthemums, and gerberas. High-density plants are made easier by substrate culture, which also minimizes water and fertilizer loss. Additionally, hydroponics guarantees a pathogen-free environment, improving ornamental crops' appearance and post-harvest quality (Savvas *et al.*, 2013).

Medicinal and Aromatic Plants

Hydroponic cultivation works well for medicinal and aromatic plants (MAPs), including ginseng, peppermint, basil, and thyme. Essential oil content, active chemical concentrations, and biomass output are all enhanced by regulated nutrient supply and environmental factors (Banerjee & Adenaeuer, 2014). Additionally, year-round harvesting is made possible by hydroponic MAP culture, which significantly lessens soil-borne pathogen and heavy metal pollution (Gruda, 2019). Therefore, hydroponics and soilless culture have transformed horticulture production in a variety of crop categories, promoting high-quality, space-efficient, and sustainable agriculture.

Urban Agriculture and Vertical Farming

Vertical farming (VF) and urban agriculture (UA) are quickly gaining traction as ways to address the rising need for food in crowded urban areas. These methods improve productivity, decrease food miles, and promote sustainability by incorporating hydroponics and soilless farming within urban buildings.

Multi-Layer Production Systems

To increase output per unit area, vertical farming makes use of multi-layered growth systems. Leafy vegetables, herbs, and small fruit harvests can be grown under controlled conditions using stacked trays, towers, or racks (Banerjee & Adenaeuer, 2014). When compared to traditional agriculture, multi-layer systems increase land-use efficiency by ten to twenty times and allow for year-round output (Despommier, 2010). Because of their low substrate volume and great water-use efficiency, hydroponic and aeroponic systems are best suited for multi-layer designs (Kozai *et al*., 2016).

Integration with Urban Structures

Rooftops, shipping containers, warehouses, and abandoned buildings may all be used by urban agriculture to produce crops locally (Specht *et al*., 2014). While warehouse-based VF enables fine environmental control, shielding crops from pests, harsh weather, and pollution, rooftop farms enhance urban microclimates and offer insulation (Kalantari *et al*., 2017). Circular urban ecosystems are encouraged and land acquisition expenses are reduced by integration with current infrastructure.

Smart Farming Tools: Automation, Robotics, and AI

Vertical farming practices are changing due to automation, robots, and artificial intelligence. While AI-driven systems manage lighting, watering, and fertilizer supply, sensor networks keep an eye on pH, EC, temperature, and humidity (Shamshiri *et al*., 2018). Transplanting, harvesting, and packing are supported by robotic arms and self-driving cars, which save labour costs and increase productivity (Al-Kodmany, 2018). Scalable urban agriculture is made possible by smart farming instruments, which also increase production and decrease mistakes.

Energy Use and Efficiency Strategies

In vertical farms, energy demand is a significant problem, mostly because of pumps, lights, and climate control. LED illumination allows for light spectrum optimization for growth while consuming less power than fluorescent or high-pressure sodium lamps (Morrow, 2008; Bantis *et al*., 2018). Energy storage options, solar energy integration, and energy-efficient HVAC systems all contribute to lower operating costs (Kozai *et al*., 2016). Vertical farming may become more sustainable by increasing energy usage efficiency through the optimization of light scheduling and heat recovery (Despommier, 2013).

Advantages, Constraints, and Economic Implications

Adoption of hydroponics and soilless farming is heavily influenced by economic feasibility. Even while the initial costs are greater than with traditional soil-based systems, profitability may be guaranteed with careful planning and effective maintenance, especially for high-value crops and urban agricultural projects.

Cost of Setup and Operation: The technology, crop kind, 9o and size all affect how much hydroponic systems cost. Building greenhouses or polyhouses, fertigation and irrigation systems, climate control, lighting, and automation infrastructure are examples of capital costs (Resh, 2022). Nutrient solutions, power, labour, water, and maintenance are examples of operating expenses. According to (Banerjee and Adenaeuer 2014) and (Kozai *et al*., 2016), setup expenses for small-scale urban growers are between $50 and $200 per square meter, whereas big commercial farms may need between $300 and $500 per square meter, depending on their level of complexity. Long-term operating expenses can be decreased by automation and energy-efficient devices such smart sensors and LED lights (Shamshiri *et al*., 2018).

Yield and Productivity Comparison: Generally speaking, soilless and hydroponic methods yield more per unit area than soil-based production. Due to improved nutritional delivery, less pest pressure, and year-round production, leafy vegetables and herbs can produce two to five times as much (Sambo *et al*., 2019; Barbosa *et al*., 2015). In comparison to conventional soil farming, hydroponics produces fruiting vegetables like tomatoes and cucumbers with earlier harvest cycles and better quality (Gruda, 2019). Hydroponics is appealing for urban and space-constrained agriculture since multi-layer vertical systems increase production even more (Banerjee *et al*., 2015).

Market Opportunities for Hydroponic Produce: Globally, there is a growing demand from consumers for locally farmed, fresh vegetables free of pesticides. According to Specht *et al*. (2014), hydroponically grown vegetables, herbs, berries, and microgreens serve upscale markets and urban consumers who value quality and convenience. High-value crops like strawberries, ornamentals, and medicinal plants can be produced with an eye toward export, providing new sources of income (Teixeira da Silva & Dobránszki, 2014). Urban farms that are close to cities are more competitive because they lower transportation expenses.

Profitability Models for Small and Large Growers: Crop choice, system effectiveness, and market access all affect profitability. While big commercial farms profit from economies of scale, small-scale producers can concentrate on high-value crops and specialty markets to optimize profits per square meter (Kozai *et al.*, 2016; Despommier, 2010). Hydroponic systems can reach break-even thresholds in two to five years with efficient fertilizer and energy management, according to sensitivity analysis and cost-benefit models. Depending on crop and market circumstances, these systems may have net margins of 20 to 40% (Al-Kodmany, 2018; Morrow, 2008).

While hydroponics and soilless farming have many advantages over conventional farming, there are drawbacks that affect their uptake and financial success. Comprehending these variables is essential for choosing appropriate crops and creating effective systems.

Benefits and Challenges: When compared to traditional soil-based farming, hydroponic systems offer significant water-use efficiency, frequently cutting water use by 70–90% (Resh, 2022; Kozai *et al.*, 2016). Accurate nutrient distribution leads to increased yields per unit area, quicker crop cycles, and consistent growth (Sambo *et al.*, 2019). When combined with greenhouses, vertical farms, or controlled settings, these solutions allow for year-round production regardless of temperature or season (Despommier, 2010; Banerjee & Adenaeuer, 2014). When there are no soil, soil-borne illnesses and pests are eliminated, which lowers the need for pesticides and increases product safety (Raviv & Lieth, 2008). Additionally, hydroponics maximizes space in highly populated regions by enabling vertical farming and urban agriculture (Specht *et al.*, 2014; Kozai, 2013).

Infrastructure, climate control, and automation systems are among the high setup and ongoing expenses of hydroponics, despite its benefits (Banerjee *et al.*, 2015; Al-Kodmany, 2018). Water quality, pH, EC, and nutrient solutions all demand technical know-how (Raviv & Lieth, 2008; Shamshiri *et al.*, 2018). Because diseases can spread quickly through shared nutrient solutions, hygiene and close observation are essential (Gruda, 2019). Particularly in vertical farms and indoor systems, energy usage may be substantial, notably for lighting and climate management (Morrow, 2008; Bantis *et al.*, 2018).

Suitability Based on Crop Type and Climate: High-value, quick-growing crops including green vegetables, herbs, strawberries, and ornamentals are most suited for hydroponic systems (Resh, 2022; Teixeira da Silva & Dobránszki, 2014). Fruiting crops can reach great yield under regulated conditions, although they may need more complicated management (Gruda, 2019). System selection is influenced by climate; integration with greenhouses or temperature-controlled facilities increases productivity and safeguards crops in hot or cold climates (Kozai *et al.*, 2016; Specht *et al.*, 2016).

Sustainability, Environmental Impact, and Emerging Technological Prospects

In hydroponics and soilless farming, sustainability is a crucial factor that affects long-term viability, environmental effect, and resource efficiency. The goals of advanced systems are to limit chemical inputs, incorporate renewable energy, and eliminate water and nutrient waste. Closed-loop hydroponic systems that recycle nutrient solutions and minimize discharge significantly improve water-use efficiency and reduce environmental contamination compared to conventional farming. Integrating renewable energy sources such as solar and wind further lowers the carbon footprint of energy-intensive components like pumps, lighting, and climate control, while advanced technologies including efficient HVAC systems and LED lighting enhance overall sustainability. The adoption of eco-friendly substrates such as cocopeat, perlite, and composted organic media also contributes to reduced environmental impact, especially when paired with responsible waste management practices like composting and reuse of spent materials to support circular nutrient cycles. Additionally, organic hydroponic approaches that use microbial inoculants and biofertilizers decrease dependence on synthetic fertilizers, enhance substrate microbial activity, and align with consumer demand for environmentally responsible food production, collectively enabling high yields with minimal ecological burden.

Rapid technological innovations are transforming hydroponics and soilless cultivation by enabling greater efficiency, precision, and adaptability across diverse growing environments, ultimately supporting the broader sustainability and scalability of urban agriculture. Artificial intelligence and machine learning now play a central role in optimizing production, with predictive tools assisting in early disease detection, climate regulation, and nutrient management (Shamshiri *et al*., 2018; Li *et al*., 2021). Digital twin technology further enhances system performance by creating virtual replicas of hydroponic setups that simulate crop behavior and resource dynamics under varying conditions to guide informed decision-making (Verdouw *et al*., 2021). Real-time automated monitoring through Internet of Things sensors strengthens operational accuracy by continuously tracking pH, electrical conductivity, dissolved oxygen, temperature, and humidity while reducing labor demands (Kalantari *et al*., 2017). Parallel to these technological advances, plant breeding programs are increasingly focused on developing hydroponic-specific cultivars that exhibit traits such as compact growth, rapid development, efficient nutrient uptake, tolerance to dense planting, and resistance to waterborne pathogens, improving both productivity and resilience within controlled environments (Gruda, 2019; Barbosa *et al*., 2015). Beyond Earth, hydroponics has become fundamental to space agriculture efforts, as organizations like NASA develop closed-loop systems that prioritize nutrient recycling, water conservation, and optimized artificial lighting for sustaining crops aboard the International Space Station and future missions to Mars (Wheeler, 2017; Massa *et al*., 2017). Meanwhile, terrestrial innovations continue to expand with the rise of vertical megafarms that combine automation, environmental control, and advanced lighting technologies to support continuous, high-density production in cities (Despommier, 2013; Kozai *et al*., 2016), complemented by the growing availability of low-cost, do-it-yourself hydroponic kits that democratize participation in urban farming and offer practical solutions for resource-limited communities (Banerjee & Adenaeuer, 2014).

Conclusion

In contemporary horticulture, hydroponics and soilless agriculture have become revolutionary techniques that address issues brought on by land scarcity, climate change, and the rising demand for premium food. Significant progress has been achieved in substrate development, controlled environment integration, nutrition management, and system design in recent decades. High yields, effective water and fertilizer utilization, and year-round production are made possible by contemporary hydroponic methods, such as deepwater culture, nutrient film technology, aeroponics, and drip systems, regardless of soil availability or environmental limitations. The accuracy and effectiveness of hydroponic systems have been further improved by automation, sensor technology, and AI-driven monitoring. These developments maximize resource use, lower labour costs, and enhance crop quality. Furthermore, vertical farming systems and urban agricultural applications make effective use of constrained space, delivering fresh food near customers while lowering transit and related environmental effects. There are still difficulties in spite of these benefits. Large-scale adoption is constrained by high setup and operating costs, energy consumption, and the requirement for technical skills. Other issues include the potential for quick disease transmission in pooled nutrient solutions and the effects of non-recyclable substrates on the environment. Crop type, local climate, and market availability all affect suitability, highlighting the necessity of context-specific tactics and cautious management. In the future, soilless farming and hydroponics will be essential to sustainable urban food systems and global food security. Advanced automation technologies, eco-friendly substrates, and renewable energy integration may improve sustainability and lessen environmental impact. The adaptability and promise of these systems are further demonstrated by the creation of hydroponic-specific crop types, space agricultural applications, and affordable systems for small-scale producers. All things considered, hydroponics is a viable option for resilient, effective, and ecologically conscious food production in the twenty-first century, providing chances to satisfy the demands of expanding people while protecting natural resources.

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