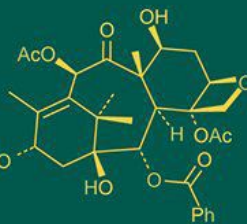
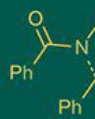
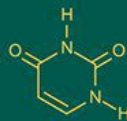
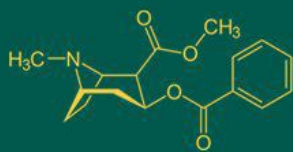


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Advancing urban horticulture through vertical farming: A global review of technologies and sustainability

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Abstract

Rapid urbanization, climate variability, and declining arable land are placing increasing pressure on conventional horticulture, prompting the development of resource-efficient production systems. Through optimized space, water, and fertilizer utilization in controlled conditions, vertical agriculture has evolved as a game-changing strategy that permits high-density, year-round crop production. Recent developments in vertical farming, such as system architecture, soilless growing methods (hydroponics, aeroponics, and aquaponics), environmental control, artificial lighting, automation, and data-driven management, are all critically examined in this study. The performance of horticultural crops, particularly green vegetables, herbs, and some fruiting species that exhibit great production and quality in vertical systems, is given considerable attention. In comparison to traditional agriculture, comparative analyses show significant savings in land and water consumption; nonetheless, high energy demand continues to be a significant barrier to sustainability and economic feasibility. Crop improvement for controlled settings, energy-efficient system design, integration of renewable energy, and standardized frameworks for sustainability evaluation are important research gaps.

Keywords: Vertical farming, urban agriculture, controlled environment agriculture, soilless cultivation, resource-use efficiency, sustainability

1. Introduction

1.1 Global Challenges in Horticultural Production

Global horticultural production including (fruits, vegetables, ornamentals, and plantation crops) faces complex climatic, biological, economic, and social challenges that threaten yield, quality, and sustainability. Climate change and abiotic stress, including rising temperatures, erratic rainfall, drought, salinity, heat waves, ^[1, 2] and altered chilling requirements, can disrupt crop phenology, flowering, fruit set, yield stability, and quality. Elevated CO₂ levels may not compensate for increased respiration, evapotranspiration, and nutrient imbalances ^[3, 4]. Pests, diseases, and chemical dependence all contribute to increased production risks, with emerging and re-emerging pathogens, pesticide resistance, and regulatory restrictions reducing the efficacy of traditional protection strategies and excessive chemical use endangering environmental and food safety ^[5, 6].

Water shortages, soil deterioration, fertilizer inefficiency, and high energy needs in protected farming all pose challenges to long-term intensification ^[7]. Finally, labor shortages, increased input costs, reliance on seasonal laborers, and supply-chain vulnerabilities all contribute to the destabilization of horticulture systems ^[8]. These interrelated stresses highlight the importance of inventive, resilient, and resource-efficient ways, making urban and vertical agriculture under regulated conditions a feasible answer for long-term horticulture production.

1.2 Emergence of Urban and Vertical Agriculture

The fast development of urban populations, limited arable land availability, and rising demand for high-quality, year-round horticultural food have all contributed to the rise of urban and vertical agriculture ^[9-11].

Vertical farming, which cultivates crops in stacked layers or multi-tiered systems, uses Controlled Environment Agriculture (CEA) to precisely manage light, temperature, humidity, CO₂ and fertiliser delivery. Hydroponics, aeroponics, and aquaponics allow for intense crop production regardless of external climatic conditions, maximising land usage and improving food security in densely populated places. Over the last decade, advances in LED lighting, automation, sensors, and smart monitoring have substantially increased the efficiency and scalability of vertical farms, establishing them as a transformational technique in modern horticulture.

1.3 Importance of Vertical Agriculture for Horticultural Crops

Vertical agriculture represents a paradigm shift in horticultural production, enabling intensive, year-round cultivation of high-value crops such as leafy greens, herbs, and small-fruited vegetables within controlled environments. By decoupling crop growth from climatic constraints, vertical systems dramatically increase yield per unit area, optimize resource use, and minimize water, nutrient, and pesticide inputs [12]. These systems enhance crop quality and nutritional content, reduce postharvest losses, shorten supply chains, and support urban food security. As global urbanization and land scarcity intensify, vertical agriculture offers a sustainable, resilient, and economically viable solution for modern horticulture, with substantial potential for widespread adoption and high-value output [13].

1.4 Objectives and Scope of the Review

To give a thorough overview of vertical and urban agriculture for horticultural crops, this study will concentrate on:

1. Modern farming practices and technological advancements.
2. Crop performance, appropriateness, and resource efficiency.
3. Environmental effects and sustainability measures.
4. Obstacles, financial factors, and societal ramifications.

Important research gaps and potential paths forward for the development of controlled-environment horticulture.

2. Framework and System Classification

2.1 Definitions and Terminologies

2.1.1 Urban agriculture

Urban agriculture is widely defined, according to the FAO and Mougeot's conceptual framework, as the cultivation of plants and the raising of animals, including aquaculture, within cities, towns, and their immediate peri-urban surroundings for sustenance, social, educational, or economic purposes [14]. It includes the complete urban food

value chain, from production to processing, distribution, and marketing of food items in urban, suburban, and peri-urban settings. Home and communal gardens, rooftop and balcony horticulture, tiny plots, livestock units, and market-oriented farms all fall under the umbrella of urban agriculture [15-17]. Although often treated as a separate category, several scholars argue that urban agriculture is not fundamentally different from conventional agriculture in biological terms; rather, it represents agricultural practices tailored to the specific spatial, infrastructural, and socioeconomic conditions of urban environments. This viewpoint emphasises its significance as an adaptable and context-dependent component of sustainable urban food systems.

2.1.2 Vertical Farming

Vertical agriculture, often known as vertical farming, is the practice of growing crops in vertically stacked layers, such as shelf systems, multi-story structures, towers, or vertical walls, with the primary goal of increasing productivity per unit land area [18-20]. These systems are mostly found in metropolitan areas and are closely related to controlled environment agriculture (CEA), in which important growth parameters like light, temperature, humidity, and carbon dioxide concentration are accurately controlled. Vertical farming is primarily based on soilless growing technologies such as hydroponics, aeroponics, and aquaponics, with artificial lighting [21, 22]. Vertical agriculture can vary in size from modest family or community-based installations to big commercial multi-level farms. Vertical farming, because of its excellent environmental control and spatial efficiency, allows for year-round production, reduced insect and disease incidence, and consistent crop quality.

2.1.3 Indoor Farming and Plant Factory

Indoor farming refers to crop production techniques that work within enclosed structures, such as greenhouses or totally closed buildings, with partial or complete environmental control. This wide category encompasses both indoor vertical farms and innovative plant manufacturing systems. Plant factories, sometimes called plant factories with artificial lighting (PFALs) or closed plant production systems (CPPS), are the most technologically advanced type of indoor farming [22]. These systems are totally enclosed and have fine control over light intensity and spectrum, temperature, relative humidity, carbon dioxide concentration, and nutrient delivery, often in multi-layered, soilless production systems that rely solely on artificial illumination [23]. Plant factories, due to their high level of environmental control, biosecurity, and production uniformity, are particularly suited for the reliable, year-round production of safe, high-quality horticultural crops, and are frequently associated with indoor vertical farming in advanced urban food production systems.

Table 1: Comparison of Vertical/Controlled Environment Production Systems

System Type	Production Environment	Light Source	Degree of Environmental Control	Energy Demand	Key Advantages	Major Limitations
Fully controlled indoor systems	Completely enclosed indoor facilities	Artificial (LED)	Very high (full control)	High	Year-round production, high uniformity, strong biosecurity, high resource-use efficiency	High energy demand, high capital cost
Semi-controlled systems	Greenhouses, rooftop farms	Natural + supplemental LED	Moderate	Medium	Lower energy use, reduced investment cost, weather buffering	Seasonal yield variability
Hybrid vertical systems	Partially enclosed vertical structures	Natural + artificial	Moderate to high	Medium	Improved space efficiency, flexible operation	Partial climate dependence

2.2 Classification by Structural Design

Urban and vertical agricultural systems can be characterised systematically according to their structural layout, which influences space usage, production intensity, and scalability. Structural design is crucial for improving plant density, light dispersion, ventilation, and operating efficiency in controlled conditions.

2.2.1 Multi-Tier Rack Systems

Multi-tier rack systems, also known as multi-tiered grow racks (MTGR), are made up of vertically stacked horizontal growth beds put in climate-controlled rooms or greenhouses to increase productivity per unit floor area ^[23, 24]. These systems often use permanent or adjustable rack structures to support soilless growing methods like nutrient film technique, flood tables, or aeroponic systems, with each tier outfitted with specialised LED lighting and watering. Multi-tier rack systems are commonly employed in indoor vertical farms and plant factories due to their remarkable land-use efficiency and suitability for intensive horticultural output.

2.2.2 Vertical Shelving and Container Farms

Vertical shelf-based systems and container farms are compact, modular alternatives to vertical agriculture, well-suited for space-constrained urban contexts. Vertical shelves, columns, and A-frame designs place plants on vertical planes or tower-like supports, with nutrient solutions provided via downward-flowing channels or columns, often using hydroponic or aeroponic techniques ^[25]. These designs include spinning A-shaped towers, vertical conveyor systems, column farms, and green-wall or facade-integrated shelves, all of which aim to maximise plant density while conserving floor space. In contrast, container farms use insulated shipping containers that have been converted with multi-tier shelving, LED lighting, climate control, and automatic watering to serve as completely enclosed, plug-and-play controlled environment agriculture (CEA) units ^[26]. Container farms, often deployed as standardised 20-40-foot modules, enable quick installation, mobility, and year-round food production in non-traditional locations, such as roofs, parking lots, and vacant urban lots. While both systems offer high flexibility, localised food production, and ease of deployment, their small production scale, constrained workspace, and higher energy and capital costs per unit area compared to larger multi-tier indoor farms may limit their economic viability for large-scale commercial applications. ^[24]

2.2.3 Container-Based Vertical Farming Systems

Container farms provide transportable, plug-and-play plant factories by retrofitting shipping containers with insulated walls, stacked hydroponic racks (typically utilizing the nutrient film technique (NFT)), LED lighting, and complete temperature control ^[27]. High yields per unit footprint are made possible by these systems; according to recent research, NFT container farms may produce leafy greens up to 11 times more productively than conventional protected horticulture. Modularity, scalability, and quick deployment are among its main benefits; its drawbacks include limited floor space, comparatively high energy consumption, and reliance on complex controlled-environment agriculture (CEA) equipment ^[28]. Container-based vertical farming offers a flexible, high-efficiency solution for decentralized urban horticulture and year-round crop production by

combining standardized infrastructure with precise environmental and nutritional management.

2.2.4 A-Frame and Vertical Column Systems

Instead of using stacked flat benches, vertical farming can use inclined or vertical growth surfaces to maximise crop density and floor area usage. Nutrient solution drips or sprays over plants placed around the perimeter of vertical columns, which are cylindrical or tower units. These systems boost yield per unit floor space but require precise light distribution, which is frequently supplemented by inter-canopy LEDs to guarantee uniform photosynthesis ^[29]. One of the most frequently mentioned variations of space-efficient vertical farming systems, A-frame systems place plants on slanted surfaces to produce an A-shaped structure that offers great plant density on a small footprint. Both designs preserve resource-use optimisation while improving operational flexibility and spatial efficiency, making them appropriate for urban and greenhouse-integrated vertical farms.

2.2.5 Systems with Rotating Vertical Columns

By mounting plant columns or shelves on mechanically powered carousels, rotating vertical column systems enable crops to move among areas with different ventilation, temperature, and light levels. Compared to static vertical systems, this dynamic structure is intended to improve light distribution and crop uniformity by reducing vertical gradients in photosynthetic photon flux density (PPFD) and microclimate ^[30]. In high-density installations, especially where artificial illumination predominates, rotation can improve production uniformity. Nevertheless, these advantages are outweighed by greater mechanical and technological complexity, increased energy consumption, and maintenance needs. Additionally, system movement may make it easier for insect pests and airborne infections to spread throughout plant tiers, but when strict hygiene procedures are followed, well-designed automation and less human interaction can lower the danger of contamination. As a result, while rotating systems provide physiological benefits, their operational viability necessitates rigorous biosecurity and technical optimization.

2.2.6 Facade and Vertical Wall Hydroponic Systems

Utilising hydroponic green walls or modular living wall assemblies, facade farming and vertical wall systems incorporate agricultural production into building envelopes, primarily utilizing drip-based irrigation or nutrient film technique (NFT). Agrivoltaic facades, which integrate photovoltaic panels with hydroponic plants to produce food and electricity simultaneously, are examples of advanced designs. To reduce structural loading, these systems usually use pocket structures or modular panels with integrated hydroponic pipework, pumps, and lightweight substrates. In addition to producing food, facade-integrated hydroponics offer important advantages for the urban microclimate, such as thermal insulation, sun shade, and a decrease in facade surface temperatures of around 2-11.6 °C, which enhances inside thermal comfort ^[31]. However, issues with waterproofing, intricate plumbing networks, maintenance accessibility, and guaranteeing long-term structural safety when retrofitting older structures limit widespread usage. Despite these limitations, facade-based hydroponics provide

a versatile approach to sustainable building design, urban agriculture, and climate mitigation [32].

2.2.7 Vertical Farming Systems Based on Rooftops

Building roofs are used for open-air or greenhouse hydroponic production in rooftop-based vertical farming systems, which primarily grow leafy greens, herbs, and fruiting crops like tomatoes [33]. These systems frequently function under hybrid environmental management, which combines partial temperature regulation, additional illumination, and natural solar radiation. By exchanging

heat, CO₂, and water streams with host buildings, rooftop greenhouses may be symbiotically connected, increasing total resource efficiency and permitting high, year-round yields [34, 35]. Despite their promise, adoption is hampered by high construction costs, a shortage of flat roofs that are technically sound, and strict standards for waterproofing and structural load. However, empirical research shows that rooftop vertical farms have great potential to improve urban food security, climatic resilience, and sustainable city metabolism when structural, regulatory, and financial barriers are effectively addressed.

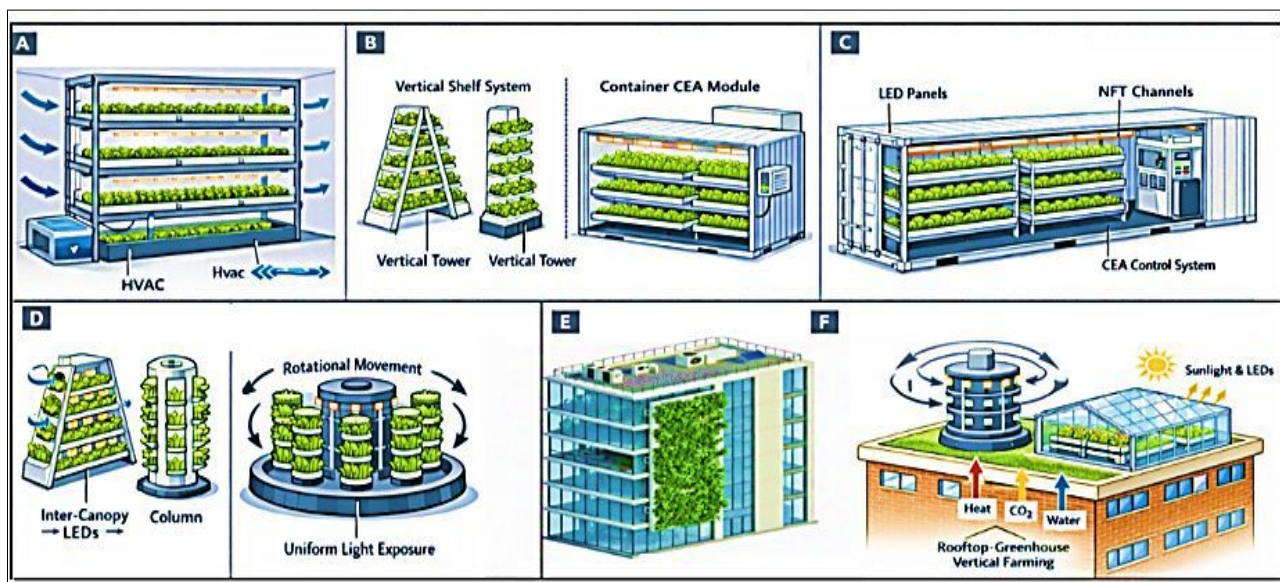


Fig 1: Representative vertical farming system configurations (A-F)

(A) Multi-tier rack system (B) Vertical shelving integrated with container-based controlled-environment agriculture (CEA) module; (C) Container-Based Vertical Farming Systems; (D) A-Frame and Vertical Column Systems; (E) Systems with Rotating Vertical Columns (F) Facade and Vertical Wall Hydroponic Systems;

2.3 Classification Based on Production Environment

The degree of environmental control imposed on crop growth, which essentially impacts production stability, resource-use efficiency, energy consumption, and resilience to external climatic unpredictability, may be used to categorize vertical and urban farming systems. Fully controlled systems differ from semi-controlled and hybrid production settings in the degree to which light, temperature, humidity, carbon dioxide concentration, and nutrient delivery are engineered vs modified by environmental variables.

2.3.1 Fully Controlled Indoor Systems

Indoor vertical farms, plant factories, growth chambers, and modular production pods are examples of sealed, fully enclosed buildings where fully regulated indoor systems function and crop production is successfully separated from external climate conditions. These systems use sophisticated sensors, automation, and increasingly AI- and IoT-based control platforms to precisely regulate all important environmental parameters, such as light intensity and spectrum, temperature, relative humidity, carbon dioxide

concentration, air circulation, and nutrient supply [36, 37].

Photosynthesis in completely regulated systems is mostly or solely dependent on artificial illumination, particularly light-emitting diodes (LEDs), which allows complete control over photoperiod and spectrum composition [37]. This high level of environmental management enables steady year-round production, excellent crop uniformity, and predictable quality, regardless of seasonal or regional climatic variations [36, 38]. Furthermore, the contained form of these systems improves biosecurity by dramatically lowering insect and disease pressure and reducing the need for chemical plant protection measures.

Fully regulated indoor systems achieve extremely high water and nutrient efficiency using closed-loop, recirculating soilless farming systems. However, these benefits are offset by high energy demands, notably for artificial lighting, heating, ventilation, air conditioning, and dehumidification. As a result, energy optimisation, increased lighting efficiency, and integration with renewable energy sources or smart energy grids are important hurdles to the long-term sustainability and economic feasibility of fully controlled indoor vertical farming systems.

Table 2: Classification of vertical agriculture systems and their key characteristics

System type	Production environment	Light source	Degree of environmental control	Energy demand	Key advantages	Major limitations
Fully controlled indoor systems	Completely enclosed indoor facilities	Artificial (LED)	Very high (full control)	High	Year-round production, high uniformity, strong biosecurity, high resource-use efficiency	High energy demand, high capital cost
Semi-controlled systems	Greenhouses, rooftop farms	Natural + supplemental LED	Moderate	Medium	Lower energy use, reduced investment cost, weather buffering	Seasonal yield variability
Hybrid vertical systems	Partially enclosed vertical structures	Natural + artificial	Moderate to high	Medium	Improved space efficiency, flexible operation	Partial climate dependence

3. Soilless Cultivation Systems for Vertical Agriculture

Soilless cultivation systems are fundamental to vertical agriculture, as they decouple plant growth from soil and enable precise control of nutrients, water, oxygen, and root-zone conditions in vertically stacked environments. These

technologies prevent soil-borne illnesses, improve resource efficiency, and make automation easier. Hydroponics, aeroponics, and aquaponics are the main soilless techniques used in vertical farming.

Table 3: Comparative Overview of Vertical/Controlled Environment Farming Systems

System Type	Typical Configurations (Vertical/CEA)	Yield & Productivity	Water-Use Efficiency & Nutrient Cycling	System Complexity & Limitations
Hydroponic (NFT, DWC, substrate)	Multi-tier NFT channels, DWC rafts, ebb-flow/drip substrate beds under controlled climate & LED lighting	High and consistent yields for leafy greens and herbs; ~3.5-4x higher than soil systems	Efficient nutrient reuse; water-use efficiency 70-90% higher than soil	Moderate complexity; requires nutrient/pH management and disease/water quality monitoring
Aeroponic	High-pressure fine mist nozzles in stacked vertical racks, roots hanging in air	Faster growth and higher biomass than hydroponics; 20-30% increased growth in leafy crops	Exceptional water conservation; up to 95% lower water use vs conventional farming	High complexity; sophisticated infrastructure, risk of nozzle clogging, power dependency, advanced controls needed
Aquaponic (coupled/decoupled)	Integrated fish tanks with hydroponic NFT/DWC media beds; biofilters for nutrient conversion	Plant yields comparable to hydroponics; additional fish biomass	Very high nutrient recycling; continuous water reuse with 80-95% lower water demand; high nutrient retention	High complexity; multi-trophic management, biofiltration, solids treatment, and nutrient balance management

3.1 Hydroponic Systems

The most widely used soilless technologies in vertical farming are hydroponic systems, which grow plants in nutrient-rich aqueous solutions without the need for soil. The nutrient film technique (NFT), deep water culture (DWC), and substrate-based hydroponics are common hydroponic designs, each with unique operating benefits and drawbacks. Formulation, handling, and recycling of nutrient solutions

3.1.1 Nutrient film technique (NFT)

NFT systems maintain high oxygen availability while showering plant roots with a thin, continuously flowing film of nutritional solution that travels via shallow channels. NFT is well-liked for leafy greens since it works well with automation and vertical stacking. However, in order to preserve nutrient stability and avoid root-zone diseases, the small root-zone volume offers little buffering capacity, and the lack of a significant biofilter calls for additional filtration or biological treatment units^[38, 39].

3.1.2 Deep water culture (DWC)

DWC systems support plants on floating rafts with roots fully submerged in aerated nutrient solution. For crops like lettuce and basil, as well as in commercial aquaponic operations, this arrangement is popular because it offers a stable root environment^[40]. As long as proper oxygenation is maintained, DWC systems are comparatively easy to maintain, show good yield stability, and provide robustness against transient nutrient or flow variations.

3.1.3 substrate-based hydroponics: In order to offer root

anchoring, aeration, and partial biofiltration, substrate-based systems use inert growth material like cocopeat, perlite, or rockwool. These systems work well for a larger variety of crops, such as fruiting vegetables, but they need more frequent upkeep, substrate renewal, and careful watering control to prevent salt buildup.

3.1.4 Formulation, management, and recycling of nutrient solutions

In hydroponic systems, precise fertilizer formulation, electrical conductivity (EC), and pH management are crucial factors that determine production and quality. as combined with fertilizer recycling and condensate water recovery from dehumidification systems, closed-loop fertigation may more than quadruple water-use efficiency as compared to traditional farming. It has been demonstrated that sophisticated techniques like split-root NFT setups and customized EC regimes may boost lettuce production while lowering physiological conditions like tip burn.

3.2 Aeroponic Systems

Aeroponic systems provide remarkable root-zone oxygenation and quick nutrient absorption by delivering nutrients directly to suspended roots through tiny misting. When compared to substrate-based and traditional hydroponic systems, this arrangement significantly increases water-use efficiency, boosts metabolic activity, and speeds up growth rates. Nutrient availability, root health, and overall system performance are all significantly influenced by controlled misting frequency and droplet size.

Aeroponic systems have several operating difficulties that limit their commercial scalability, despite their

physiological benefits. Because short-term failures can quickly cause root desiccation and crop loss, system dependability is heavily dependent on a steady power supply and accurate misting management. Nozzle clogging, unequal nutrition distribution in thick root systems, and

increased capital and maintenance expenses are other constraints. As a result, even though aeroponics has a great potential for production under ideal circumstances, its use in vertical agriculture is still constrained by risk sensitivity and technological complexity.

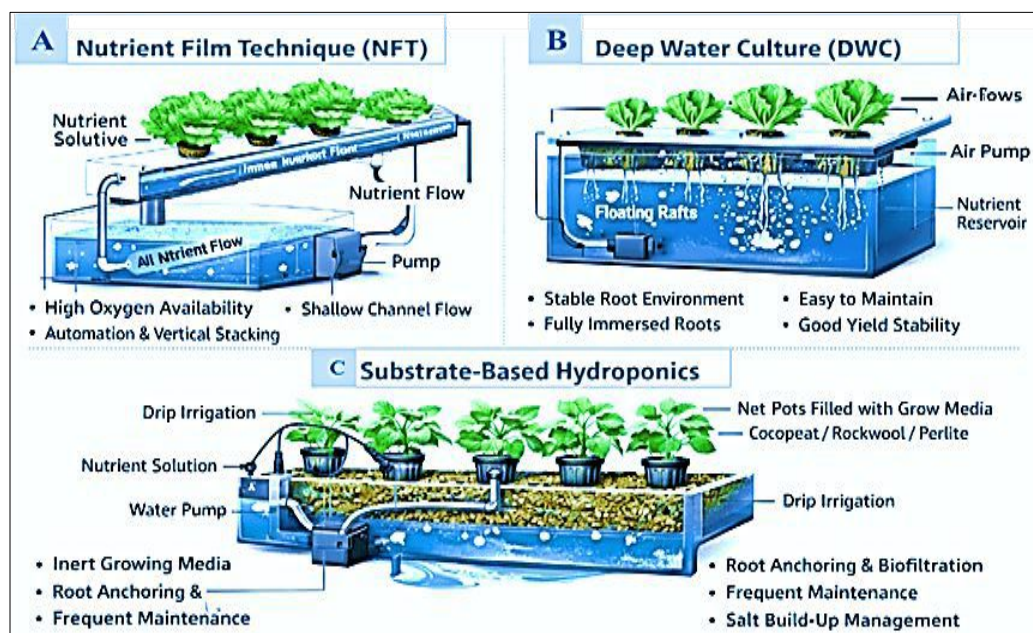


Fig 2: Major hydroponic cultivation systems (A-C)

(A) Nutrient Film Technique (NFT) system; (B) Deep Water Culture (DWC) system; (C) Substrate-based hydroponic system.

3.3 Aquaponic and Integrated Systems

Through microbial nitrification of fish-derived ammonia into plant-available nitrate, aquaponic systems combine hydroponic plant production with recirculating aquaculture to facilitate internal nutrient cycling. Aquaponics is positioned as a resource-efficient approach for urban and vertical agriculture because of this biologically connected system, which drastically lowers freshwater outflow and synthetic fertiliser inputs. For leafy crops and culinary herbs, aquaponic systems have shown yield performance similar to hydroponics under ideal conditions.

Despite these benefits, the equilibrium between fish biomass, microbial activity, and plant nutrient requirement has a significant impact on productivity and system stability. Crop performance is sometimes hampered by nutrient imbalances, especially deficits of potassium, calcium, and iron, which need external supplementation and decrease system circularity. Furthermore, because of the increased system complexity and biological risk, integrating aquaponics into multi-tier vertical constructions is still technically difficult.

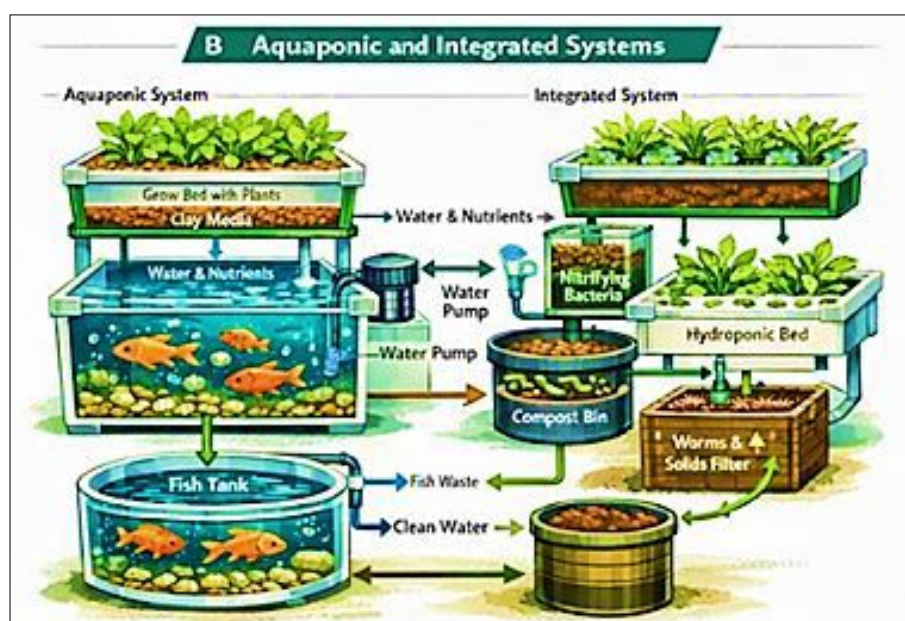


Fig 3: Major advanced soilless cultivation systems

(A) Aquaponic and integrated production system.

4. Enabling Technologies in Vertical Agriculture

4.1 Environmental Control Technologies

To keep crops within ideal physiological limits, environmental control in vertical farming depends on automated control systems and extensive sensor networks to continually monitor and regulate temperature, relative humidity, CO₂ concentration, and airflow^[41, 42]. Because vertical gradients in temperature, humidity, and CO₂ form throughout crop tiers and change over time within protected buildings, stratified environmental management is crucial. It has been demonstrated that CO₂ enrichment to around 800 $\mu\text{mol}\cdot\text{mol}^{-1}$ maximizes lettuce biomass accumulation, with declining yield responses at higher concentrations, making precise control of atmospheric composition especially crucial^[43]. In high-density vertical farming systems, integrating real-time sensors, zone-specific management, and adaptive algorithms improves crop production, resource efficiency, and environmental homogeneity.

4.2 Systems of Artificial Lighting

Light-emitting diodes (LEDs) are essential for optimizing production in vertical farming systems because they allow for fine control over spectrum composition, light intensity, and photoperiod. In crops like lettuce and basil, increasing photosynthetic photon flux density (PPFD) significantly increases biomass accumulation^[44]; nevertheless, this advantage is accompanied with proportionately increased energy consumption. Crop performance is further influenced by spectral optimization; it has been demonstrated that supplementing white light with deep red (≈ 660 nm) and far-red (≈ 730 nm) wavelengths increases yield, leaf number, and canopy expansion while perhaps causing morphological responses such as stem elongation^[45]. According to recent assessments, feasible lighting "recipes" for leafy greens are focused around 200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ PPFD with a 16-hour photoperiod and blue-red-dominant spectra, balancing crop quality, productivity, and energy efficiency in controlled environments.

4.3 Digital Technologies, Automation, and Sensors

Continuous, real-time data collection on microclimate variables, light intensity, and fertilizer solution dynamics in vertical farming systems is made possible by Internet of Things (IoT) networks. Automated control architectures collect these data streams and use actuators to dynamically adjust CO₂ enrichment, LED lighting, HVAC systems, and irrigation with little assistance from humans^[46, 47]. By facilitating early illness identification, yield prediction, climatic set-point optimization, and predictive maintenance, artificial intelligence and machine learning (AI/ML) models further improve system performance. These models are being integrated into digital twin systems that model crop and microclimate reactions before deployment, enabling proactive, risk-reduced decision-making. In controlled-environment agriculture, IoT-driven automation and AI-enabled control frameworks work together to increase operational resilience, resource efficiency, and output consistency.

4.4 Precision Fertigation and Nutrient Monitoring

In order to keep nutrient solutions within certain ideal ranges and minimize labor needs and dosing mistakes, vertical farming systems use electrical conductivity (EC) and pH sensors in conjunction with feedback controllers or

fuzzy-logic algorithms^[48]. Recent advancements go beyond straightforward feedback loops to predictive analytics frameworks that concurrently control temperature, pH, EC, and solution volume, allowing for quicker and more accurate nutrition modifications^[49]. According to scoping assessments, these integrated control systems greatly reduce fertilizer loss and system downtime while increasing crop uniformity, solution stability, and nutrient-use efficiency. Thus, a key element of high-performance soilless cultivation in vertical agriculture is precision fertigation, which is backed by sophisticated sensing and intelligent management. (e.g., 1.0-2.0 dS·m⁻¹ for many hydroponic crops). Classical proportional-integral-derivative (PID) controllers are gradually being supplemented or replaced by fuzzy-logic and fuzzy-PID systems, which can better handle the nonlinear, time-lagged dynamics of fertigation and persistent pH drift. These controllers adjust pump operation or solenoid valve actuation in response to EC/pH changes, significantly decreasing human measurement and dosage mistakes. Recent scoping reviews show a shift away from single-variable feedback control and toward multi-variable predictive frameworks that manage pH, EC, solution volume, and temperature using regression-based or model-predictive control approaches, allowing for faster, more accurate, and robust nutrient dosing. Case studies consistently show that sensor-driven precision fertigation saves water and nutrients, often by 30 to 40%, while also increasing yield, nutrient productivity, and uniformity when compared to timer-based or empirical management, particularly in IoT-enabled vertical hydroponic systems^[47].

5. Suitability and Performance of Horticultural Crops

5.1 Crop Selection Criteria

Crop selection for vertical farming depends on biological appropriateness, technological feasibility, and market profitability. Current systems tend to favor quick, compact, and high-value species.

5.1.1 Growth Cycle and Morphology

Vertical farming techniques emphasize short-cycle, compact crops like leafy vegetables, herbs, and microgreens, which fit within thick multilayer designs and allow for many harvests per year^[25, 50]. Crops having a narrow canopy spread, quick early development, and low structural biomass enhance space use. Large woody perennials and tree fruits, on the other hand, are often inappropriate because to their huge size, dormancy needs, and protracted juvenile stages; however, dwarf cultivars and specific rootstock techniques may increase viability in future controlled-environment production scenarios^[51].

5.1.2 Yield Potential and Resource Utilization Efficiency

According to meta-analyses, lettuce yields in controlled-environment agriculture (CEA) can be around twice as high as in open-field systems, with vertical designs delivering particularly large improvements in yield per unit ground surface^[52]. High planting-density crops, such as leafy greens, selected herbs, and some tuber crops like potatoes, produce the most edible biomass per square meter per day, indicating improved land- and time-use efficiency in vertically stacked systems^[50].

5.1.3 Energy and Environmental Demands

The high energy needs for artificial lighting and climate control severely limit crop choice in vertical farms. Species

with low light saturation values and a high economic return per unit energy input are thus preferable. This energy-productivity trade-off regularly benefits leafy crops, herbs, and microgreens, which produce economically viable yields with modest photosynthetic photon flux densities [53].

5.1.4 Marketing and Product Quality

Commercial indoor and vertical farming systems place a focus on "clean, green, and gourmet" goods such as high-quality leafy greens, culinary herbs, microgreens, and select fruit crops like strawberries [54]. Sensory and postharvest traits flavour; texture, colour, nutritional quality, and shelf life are driving emergent breeding projects aimed toward CEA-specific plant design, quality optimisation, and consumer acceptability [55].

5.2 Leafy Vegetables

Leafy vegetables are the most extensively researched and economically dominating crops in vertical farming because to their high production potential, quality consistency, and resource efficiency. Controlled-environment agriculture (CEA) yields lettuce almost twice as much as open-field systems, with vertical setups producing $\sim 6.9 \text{ kg m}^{-2}$ per crop cycle and much shorter production timeframes ($\leq 40\text{--}70$ days) [56]. Container-based NFT vertical farms have reported extreme yield intensification, with annualized outputs of $\sim 337 \text{ kg m}^{-2} \text{ yr}^{-1}$ for lettuce and $>2000 \text{ kg m}^{-2} \text{ yr}^{-1}$ for arugula [57]. Stacking and rotational systems maintain yields comparable to horizontal benches, but with superior land and energy-use efficiency [58]. Product quality in leafy greens is very responsive to environmental management; customized LED spectra and photoperiods improve vitamin C, phenolics, sugars, and leaf colors, but some spectral combinations cause morphological trade-offs such as elongation or bolting [59]. Short preharvest continuous-light treatments improve soluble protein, ascorbic acid, and sugar content even when biomass gains are low, and moderate abiotic stressors (e.g., regulated deficit irrigation) can boost antioxidant levels in lettuce and kale with minimal yield losses [60]. Vertical hydroponic and aeroponic systems provide significant water and nutrient savings for growing leafy crops. NFT systems may reduce water consumption by up to 90% compared to soil farming while maintaining steady yields of $11\text{--}14 \text{ kg m}^{-2}$ each crop [61]. Optimized planting density and prolonged low-intensity photoperiods increase light and energy efficiency, confirming green vegetables as the most ecologically and economically feasible crop category for existing vertical farming systems.

5.3 Medicinal Crops and Herbs

Herbs and medicinal plants are particularly well suited to vertical farming due to their compact morphology, high economic value, and strong responsiveness of secondary metabolism to controlled environments. By precisely controlling light, CO₂, temperature, humidity, and nutrient supply, controlled-environment agriculture including vertical farms enables year-round, standardized production, stabilizing and frequently increasing biomass and phytochemical yields in comparison to conventional cultivation systems [62]. High planting densities significantly boost fresh yield and light-use efficiency, especially in baby-leaf basil systems. Hydroponic vertical units regularly produce basil, coriander, parsley, dill, and mint within 3–4 weeks, supporting quick crop turnover and cut-and-come-

again harvesting. Multiple reviews show that manipulation of the light spectrum, CO₂ enrichment, and intentional mild stress elevates essential oils, phenolics, flavonoids, antioxidants, and vitamin C without compromising total yield [63]. Controlled environments are particularly effective for improving and standardizing medicinal quality. The significance of vertically cultivated basil, coriander, parsley, dill, and mint as functional foods is confirmed by their constant high quantities of phenolics, carotenoids, chlorophylls, and antioxidant activity. A key lever is light quality; red-dominant spectra often maximize biomass, while blue- and UV-enriched illumination, depending on the species, increases phenolic content, essential oil accumulation, and antioxidant capacity. Italian basil's chlorophyll content, carotenoids, anthocyanins, flavonoids, photosynthetic efficiency, and leaf biomass partitioning are all improved by advanced LED techniques, such as targeted night-interruption red and far-red illumination, which also increase production and medicinal quality [64, 65]. Superior nutritional and antioxidant qualities under LED illumination are frequently demonstrated in comparisons between LED, HPS, and sunshine, supporting vertical LED-based systems as quality-focused production platforms. Herbs and medicinal crops are widely acknowledged as high-margin targets for vertical farming and priority candidates for future cultivar development tailored to controlled-environment agriculture due to their high water and nutrient use efficiency, pesticide-free production, short growth cycles, strong regrowth capacity, and premium market prices [66, 67].

5.4 Fruiting Vegetables

Compared to leafy crops, fruiting vegetables like tomato, cucumber, pepper, strawberry, and eggplant have a higher commercial value in vertical farming but are still limited by physiological, architectural, and energy constraints. Meta-analyses of the production of tomatoes and strawberries show that controlled-environment systems, such as greenhouses and vertical farms, can yield much more and use a lot less water than field cultivation, even though they use a lot more energy and have a higher potential for global warming per unit of product [66]. Productivity in stacked systems is decreased by longer crop cycles, high structural biomass, and vining or woody growth patterns that diminish edible biomass accumulation per unit time and area. In order to maintain flowering and fruit set, fruiting crops also need high daily light integrals [50]. In indoor systems, tomato and pepper seedlings only show 241–333% more biomass when DLIs reach $\sim 24\text{--}32 \text{ mol m}^{-2} \text{ d}^{-1}$, which is significantly more than what leafy greens require and directly increases electricity demand [68]. Productivity per unit energy input is often lower than that of leafy vegetables and herbs, even though optimized vertical hydroponic tomato and cucumber systems may equal yields of high-tech greenhouses with precision lighting, CO₂ enrichment, and root-zone management. When compared to high-pressure sodium lighting or sunlight, controlled environments consistently improve fruit quality: customized LED spectra and timing improve soluble solids, acidity balance, vitamin C, carotenoids, polyphenols, firmness, and sensory attributes; far-red-enriched intracanopy and morning/evening supplementation enhance flavor and nutritional metabolites without significant energy costs [68, 69]. Economic viability is further constrained by engineering issues such as restricted stacking density, structural support, pruning intensity, and

pollination needs. In commercial vertical farms, however, recent developments in breeding and gene editing for compact, dwarf, fast-cycling tomato ideotypes have reduced space occupation by up to 85% and increased effective yield by ~180%, indicating a promising pathway to overcoming architectural and energy-efficiency barriers [70]. Fruiting vegetables are currently best suited for single-layer indoor production, rooftop greenhouses, or hybrid vertical greenhouse systems; complete vertical deployment will depend on further advancements in plant ideotype design and illumination efficiency.

6. Resource-Use Efficiency

6.1 Water-Use Efficiency

Through closed-loop hydroponic and aeroponic irrigation, where fertigation solutions are constantly recirculated and almost all leachate is collected, vertical farming systems achieve remarkable water-use efficiency. According to quantitative comparisons, lettuce cultivated in vertical farms can minimize nutrient losses while requiring as little as ~1 L kg⁻¹ fresh weight, as opposed to 10-20 L kg⁻¹ in greenhouse systems and over 250 L m⁻² yr⁻¹ in open-field farming [71]. Ebb-and-flow and aeroponic vertical systems achieve water productivities of 28.1 and 52.9 g fresh weight per liter, respectively, according to experimental experiments that further highlight system-level variations [72]. Water-use efficiency may be increased by more than 200% and irrigation water demand can be reduced by up to 67% by integrating auxiliary water recovery techniques, such as condensate capture from HVAC systems [73]. In addition to decreased eutrophication potential, life cycle studies of closed-loop rooftop and vertical systems reveal further advantages, such as ~40% reductions in irrigation water consumption and 35-54% savings in fertilizer inputs compared to linear (non-recirculating) systems [74]. All of these results point to vertical farming as one of the most water-efficient horticultural production methods, which is especially useful in urban and water-constrained settings.

6.2 Energy-Use Efficiency

The main factor limiting vertical farming's sustainability and scalability is energy consumption, with artificial lighting and HVAC/dehumidification systems consuming the majority of the electricity used. Due in large part to constant artificial lighting and climatic control, comparative analyses show that lettuce grown in vertical farms usually requires 15.6-20.4 kWh kg⁻¹ fresh weight, significantly more than the 4.5-10.5 kWh kg⁻¹ fresh weight recorded for greenhouse systems [75]. Photosynthetic photon flux density (PPFD) is the primary driver of crop yield and energy load, according to dynamic modeling studies. After about 500 μmol m⁻² s⁻¹, biomass accumulation approaches saturation while energy consumption increases linearly, drastically decreasing marginal energy-use efficiency. In order to balance growth and electricity usage, energy optimization solutions place a strong emphasis on moderate PPFD in conjunction with extended photoperiods, accurate spectrum tuning, and temperature set-points close to 24 °C. With case studies showing electricity demand reductions of up to 75% and specific climate-control energy savings of roughly 20-22%, advanced environmental control algorithms, adaptive shelf configurations, and integrated climate-management systems have shown significant efficiency gains. These results

highlight the need for comprehensive optimization of lighting regimes, thermal management, and intelligent control systems rather than boosting instantaneous light intensity in order to improve energy-use efficiency in vertical farming.

6.3 Productivity on Land and in Space

By transforming horizontal growing area into stacked, volumetrically optimized production space, vertical farming systems significantly increase land and space productivity. Lettuce yields in vertical farms can reach about 150 kg m⁻² yr⁻¹, significantly higher than those in greenhouse systems (~41 kg m⁻² yr⁻¹) and open-field farming (~3.9 kg m⁻² yr⁻¹), according to quantitative comparisons [71]. Additionally, vertical systems generate an average of 6.88 kg m⁻² every crop cycle, which is more than 3.5 times higher than field-based yields, according to meta-analytical data [52]. When compared to single-layer flat systems, multilayer rack designs usually increase effective cultivable area by 200-400% while preserving similar per-layer productivity. The ultimate limits of space intensification are demonstrated by theoretical controlled-environment scenarios, which predict 220-600-fold yield improvements over field production for commodities like wheat and allow for more than ten production levels for vegetables and grains [76]. These results highlight the unmatched ability of vertical farming to enhance food yield per unit land area, especially in urban areas where horizontal space is restricted, even if such great intensification is practically limited by energy and capital needs.

7. Environmental Sustainability Implications

7.1 Carbon Footprint and Greenhouse Gas Emissions

Carbon footprint and greenhouse gas emissions are major sustainability issues since vertical farming systems are often energy-intensive despite their high production per unit area. According to life cycle assessment studies, carbon footprints from commercial vertical lettuce farms range from 0.9 to over 8 kg CO₂-eq kg⁻¹, which is frequently 5-16 times higher than open-field production and 2-7 times higher than greenhouse production when fueled by electrical grids that rely heavily on fossil fuels [77]. 80-91% of all emissions are caused by electricity, which is mostly used by LEDs and HVAC/dehumidification systems. The median operating emissions of urban and building-integrated agriculture, according to meta-analyses, are consistently greater than those of greenhouse or soil-based systems, at about 1.1 kg CO₂-eq kg⁻¹. Grid decarbonization and the integration of renewable energy, however, significantly improve sustainability results. For example, vertically grown lettuce in Norway achieved about 70% lower emissions than imported produce, and vertical farms in Finland that combined waste-heat recovery with renewable electricity showed the lowest climate impact of all systems examined [78]. In a similar vein, a case study from Scotland showed that grid decarbonization reduced emissions from 1.49 to 0.42-0.33 kg CO₂-eq kg⁻¹, bringing the effects of vertical farming on par with or lower than those of traditional open-field cultivation [79]. In order to lower carbon intensity while preserving yield and operating efficiency, mitigation solutions therefore give priority to low-carbon energy

sources, better lighting and HVAC management, adaptive climate control, and integration of waste-heat recovery.

7.2 Recycling of Waste and Nutrients

The closed-loop hydroponic and aeroponic systems used in vertical farming significantly lower nutrient losses, runoff, and related eutrophication, making them some of the most ecologically friendly food production methods. Compared to linear or free-drain systems, closed-loop rooftop and indoor hydroponic systems may save around 40% of irrigation water and 35-54% of fertilizer inputs, while significantly reducing the nitrogen and phosphorus losses that cause aquatic eutrophication, according to empirical and life-cycle research^[80]. In comparison to open-field agriculture, recirculating nutrient solutions in vertical farms further reduces the possibility for eutrophication by about 70-90%^[72]. Soilless closed-loop systems are repeatedly found to be the most efficient technique to achieve nearly zero emissions of phosphate and nitrate^[81]. When compared to open systems and soil cultivation, advanced aeroponic and sensor-controlled recirculating systems for lettuce minimise fertiliser solution consumption by 3-6×, with much fewer hazards of surface and groundwater pollution^[82]. Similarly, compared to traditional fertigation, PLC-based closed soilless systems that reuse up to 20% drainage preserve cucumber output and quality while increasing water-use efficiency by about 50%^[83]. IoT-enabled precision nutrient management, real-time EC, pH, and ion composition sensing, and model-predictive control further improve recycling efficiency^[84], resulting in a ~15% reduction in fertilizer waste and a 20% increase in leafy greens and herb yields^[85]. In addition to internal recycling, new circular economy approaches incorporate urban organic waste streams into vertical farming systems. Life-cycle analyses show that substituting conventional fertilizers and substrates with compost, brewer's spent grain, biogas digestate, aquaponic effluents, or wastewater-derived nutrients like struvite and urine-based fertilizers can reduce fertiliser-related environmental impacts by >60-66% while maintaining productivity^[86]. When taken as a whole, these developments show that vertical farming may function as a low-pollution, circular nutrient system, greatly separating crop production from nutrient losses and environmental deterioration in urban and peri-urban settings.

7.3 Participation in Urban Food Security

Urban agriculture, including vertical farming, may significantly improve urban food security and system resilience, mostly as an addition to traditional rural supply chains rather than their replacement. Vertical and rooftop farms significantly reduce reliance on lengthy, centralized, and disruptive food networks by localizing production within or close to cities^[87]. This is an advantage that becomes crucial during pandemics, geopolitical conflicts, climate extremes, or fuel and logistics shocks. According to empirical research, urban and building-integrated agriculture may use up to 90% less water and cut transportation distances by up to ~68% when compared to traditional

supply chains that span more than 2,000-2,400 km. This makes it possible to produce food even in areas with acute rural water shortage. Family-scale vertical farming may boost home vegetable and fruit self-sufficiency by about 21% and enhance city-scale self-reliance by about 2.5%, according to modeling studies in Shanghai^[88]. This would provide a quantifiable buffer against disruptions in external supply. In the face of droughts, floods, and heat waves all of which pose a growing danger to field agriculture due to climate change controlled-environment vertical farms sustain steady yields because they are essentially disconnected from weather fluctuation. As a result, urban agriculture, which includes vertical farming, is often referred to as "critical infrastructure" that decentralizes food production into several redundant nodes, lowering systemic vulnerability and boosting resilience across the urban food system. When long-distance transportation and wholesale markets were interrupted during the COVID-19 epidemic, indoor, rooftop, and vertical farming proved to be crucial advantages for preserving access to fresh, perishable foods^[89]. Together, our results show that vertical farming plays a strategically significant role in enhancing urban food availability, resilience, and adaptive capacity amid increasing environmental and socioeconomic instability, even though it cannot alone provide basic calorie demands.

8.1 Capital and Operational Costs

High capital intensity and energy- and labor-heavy operations represent the principal economic bottlenecks for vertical farming, with current commercial viability largely restricted to fast-growing, high-value leafy crops, microgreens, and herbs^[90]. Capital expenditures (CAPEX) are dominated by building acquisition or retrofitting, multi-tier racking, hydroponic or aeroponic infrastructure, LED lighting, HVAC/dehumidification, sensors, and automation, with typical estimates ranging from ~680-1,560 USD m⁻² of growing area. Lighting accounts for ~35-55% of CAPEX, while structural chambers contribute 19-41%, resulting in total setup costs often exceeding 1,500-3,500 USD m⁻², necessitating substantial external financing. Operational expenses (OPEX) are also high: depending on the location, labor accounts for 25-39% of costs, while electricity for temperature control and lighting accounts for 12-19% of OPEX. With over 73% of OPEX coming from energy usage, smaller-scale office or experimental systems show operational costs (without labor) of about 53 EUR kg⁻¹ fresh biomass, more than twice as much as large-scale vertical or field systems^[91]. Only crops with quick growth, high market value, and advantageous photon-to-price ratios are profitable, according to meta-analyses and techno-economic models; mainstays like wheat and rice are still economically uncompetitive, frequently outpacing field production costs by more than 10 times^[92]. In-depth case studies, such as those of Italian microgreen vertical farms, show positive operating margins under optimal management, but they also show that significant barriers to wider implementation include costly initial investment, reliance on power, and technical competence.

Table 4: Emerging Cost-Reduction Strategies for Vertical Farming

Strategy	Expected Effect	Citations
High-efficiency LEDs, optimized PPFD	30-50% lighting energy savings; improved Levelized Cost of Light (LCoL)	(93,94)
Smart HVACD & load shifting	15-25% HVAC energy reduction; 16-26% lighting cost reduction	(95)
Automation & digitalization	Reduces labor share; requires high upfront technology investment	(96)
Coupling with cheap/renewable energy (PV, agrivoltaics)	Partially offsets energy-driven OPEX; improves GHG emissions profile	(97)

8.3 Limitations on Crop Diversity and Scalability

Due to biological and financial constraints, vertical farming is still mostly limited to high-value, short-cycle crops. To maximise harvest frequency and saleable biomass per unit area, commercial systems primarily grow leafy greens, herbs, microgreens, berries, and a small number of compact fruiting vegetables, such as cherry tomatoes, cucumbers, and strawberries^[98]. These crops are short, quickly maturing, and highly responsive to artificial lighting in dense multilayer configurations. Larger or longer-cycle crops, such as tree fruits, vining vegetables, cereals, and tubers, on the other hand, encounter basic biophysical obstacles: tall or woody canopies lower stacking density, long crop durations lower turnover, and significantly higher light and energy requirements significantly raise production costs^[99]. Even before taking infrastructure and manpower into consideration, techno-economic and photon-cost evaluations repeatedly demonstrate that many low-value vegetables and staple crops like wheat, rice, and potatoes are not economically viable in fully illuminated vertical farms. Although initiatives to expand crop portfolios through breeding and gene editing that focus on compact design, quick cycling, and low light tolerance are beginning to take shape, these strategies are still in their infancy. High capital intensity, growing energy demand, building height and load limitations, and difficulties in providing multi-tier farms with adequate low-carbon power in urban environments all further limit scalability. As a result, current research suggests that vertical farming is economically feasible mainly in specialized, upscale urban markets and should be seen as an addition to traditional field-based agriculture for the production of large quantities of food rather than as a substitute for it.

8.4 Regulatory and Policy Concerns

The viability and scalability of vertical farming are greatly influenced by policy and regulatory frameworks; yet, governance is still dispersed over the majority of areas, which poses serious obstacles to implementation. Zoning and construction laws usually fail to accurately identify indoor vertical farms, which causes permission delays, legal confusion, and a dependency on exceptions for retrofitted or purpose-built buildings. Urban agricultural policies typically lag behind technical advancements. Calls for specific indoor-farming standards have been sparked by the identification of the lack of specified occupancy categories for indoor agriculture in model building codes as a major limitation, especially for fire safety, egress design, and mechanical systems. As demonstrated by instances like Singapore, where conflicting urban goals and intricate land-allocation processes restrict growth despite government backing for high-tech agriculture, urban land-use frameworks further restrict siting. Regulations about food safety and the environment present additional challenges. Although there is evidence that closed-loop systems can safely manage these risks with the appropriate barriers and monitoring, hydroponic and vertical systems are subject to

inconsistent standards for nutrient discharge, reclaimed water use, and microbial risk management. Energy and climate policy is especially crucial as economic viability is greatly impacted by grid constraints, high and variable power costs, and the failure to identify vertical farms as flexible or demand-responsive loads. Studies indicate that integration with demand-response markets, district heating, and renewable energy can significantly lower costs and emissions; however, these advantages rely on favorable tariff arrangements and market access. In order to reduce regulatory risk and enable the responsible scaling of vertical farming within urban food systems, recent analyses highlight the need for integrated policy frameworks that clarify zoning for indoor farms, modify building and fire codes, harmonize food-safety and water-reuse regulations for soilless systems, and incentivize energy efficiency and renewable integration.

9. Research Gaps and Prospects for the Future

Vertical farming still has significant research gaps that restrict its long-term sustainability, scalability, and efficiency despite significant advancements. The shift from high-value specialized activities to scalable, resilient elements of urban food systems will be made possible by filling these gaps. Technological innovation, agricultural enhancement, integration of renewable energy, and standardized frameworks for sustainability evaluation are important areas of study.

9.1 Technological Advancements: Automation & Energy

Energy consumption, which frequently surpasses 70% of total energy demand, is still the primary operational strain, especially for lighting and HVAC. Dynamic daily light integral (DLI), spectrum tuning, and photoperiod control are examples of adaptive LED techniques that may significantly lower energy per unit yield while preserving or increasing productivity⁽¹⁰⁴⁾. Control frameworks powered by IoT and AI also show 15-20% lighting energy reductions while increasing yield and uniformity. The necessity for next-generation integrated automation is highlighted by the fact that the majority of current systems rely on static set-points, lack multi-variable optimization, and do not fully use predictive or plant-responsive control.

9.2 Crop Enhancement in Regulated Environments

Field-bred cultivars, which are not ideal for indoor systems, are still used by the majority of vertical farms. Compact size, quick cycling, excellent light-use efficiency, and photomorphogenic plasticity under programmed light spectrum should be the goals of future breeding initiatives⁽¹⁰⁶⁾. Gene-edited tomatoes and *Nicotiana* cultivars with compact architecture can decrease space needs by 45-85% while maintaining or increasing output, boosting productivity per unit energy and footprint, according to proof-of-concept research. Breeding for indoor-specific quality features, such as antioxidant content, taste, and nutritional density, is still in its infancy but offers

a significant opportunity for crop optimization in controlled settings.

9.3 Integration of Renewable Energy

Grid reliance, operating expenses, and carbon footprints may all be considerably reduced by incorporating renewable energy into vertical farms. Although more comprehensive agrivoltaic and hybrid renewable-thermal storage designs indicate the possibility of near-net-zero energy operations, hybrid photovoltaic (PV) and storage systems presently only meet 8-12% of normal farm demand with roof-mounted P(107). In order to implement these solutions, site-specific techno-economic optimization is necessary. This includes building energy systems, seasonal resource availability, and alignment with demand-response programs.

9.4 Long-Term Sustainability Evaluations Are Necessary

Standardized long-term life-cycle analysis (LCA) and techno-economic frameworks specifically designed for vertical farms are desperately needed. In comparison to conventional systems, current research suggests carbon- or multi-impact-centric LCAs that integrate building and agricultural infrastructure, exposing trade-offs such reduced greenhouse gas emissions but greater other environmental impact. To effectively capture pollutant transfer, resource consumption, and system-level consequences and enable well-informed design and policy decisions, harmonized techniques, uncertainty quantification, and multi-criteria evaluation are crucial.

10. Conclusion

Vertical farming offers a resource-efficient and climate-resilient pathway for urban horticulture, delivering superior yield, quality, and water- and nutrient-use efficiency for short-cycle, high-value crops under controlled environments. Precision fertigation, automation, LED lighting, and multi-layer designs are examples of advanced technology that increase production while significantly lowering water use and nutrient losses. Energy demand is the biggest obstacle to widespread adoption, although high capital and energy costs, agricultural design limitations, and varied regulation frameworks continue to be significant obstacles. Integrating low-carbon energy, creating flexible and energy-efficient systems, improving indoor cultivars, and creating uniform frameworks for sustainability assessments are all necessary for future advancement. Vertical farming may develop from a specialized system into a scalable, sustainable part of urban food systems, improving food security and environmental performance, with coordinated technology innovation and supportive policy.

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