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## A Vertical Farming and Soilless Cultivation Technologies for Urban Food Security

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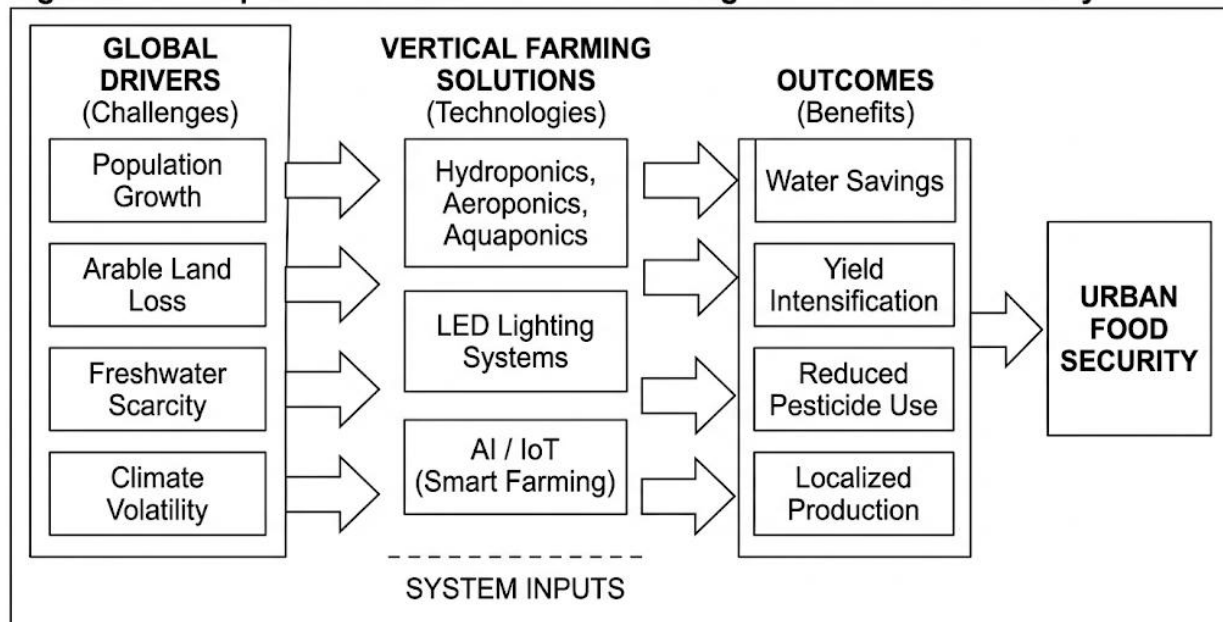
## Vertical Farming and Soilless Cultivation Technologies for Urban Food Security

**Abstract:** Vertical farming and soilless cultivation technologies represent a paradigm shift in urban agriculture, addressing the challenges of feeding a projected 9.7 billion global population by 2050 amid arable land loss (1.8–2.4% annually), freshwater scarcity (70% agricultural use), and climate volatility. This review synthesizes advancements in hydroponics, aeroponics, and aquaponics decoupling production from soil via nutrient film technique (NFT), deep water culture (DWC), and vertical stacking enabling year-round yields up to 390 times higher than traditional methods per unit area, with 70–95% water savings and reduced pesticide needs. Key innovations include LED-optimized spectral lighting (e.g., red:blue ratios for photosynthesis), AI-driven climate control (sensors for pH, EC, CO<sub>2</sub>), and integrated pest management (IPM) with beneficial microbes. Economic analyses indicate viability in urban settings (ROIs of 3–5 years for leafy greens), while environmental benefits encompass lower carbon footprints (via localized production) and enhanced food security in megacities. Challenges like high energy demands (addressed by renewables) and initial costs are mitigated through modular designs and subsidies. The integration of these systems promises resilient, localized food chains, aligning with SDGs for zero hunger and sustainable cities.

**Keywords:** vertical farming, soilless cultivation, hydroponics, aeroponics, aquaponics, urban food security, LED lighting, AI climate control, water-use efficiency, nutrient film technique, integrated pest management, carbon footprint reduction

### I. Introduction

The global agricultural landscape is currently undergoing a structural transformation, driven by the imperative to feed a population projected to reach 9.7 billion by 2050 while grappling with the systemic degradation of arable land and the volatility of climate-induced disruptions (Appicciutoli et al., 2025). Traditional land-based agriculture, which accounts for 80% of global deforestation and consumes the vast majority of accessible freshwater, is increasingly viewed as a brittle system incapable of ensuring long-term urban food security (Chen, 2025). In response, soilless cultivation and vertical farming have emerged not merely as supplemental methods, but as a comprehensive technological paradigm that decouples food production from the constraints of geography, seasonality, and ecological health (Lakhiar et al., 2025). This transition represents a fundamental shift from agrarian dependency to industrial-scale precision biological engineering, where variables from spectral composition to the microbial environment of the rhizosphere are subject to digital regulation (Tuxun et al., 2025). Vertical farming integrates advanced technologies to address urban food security challenges, summarized in Figure I.

**Figure 1: Conceptual Framework: Vertical Farming for Urban Food Security**

## 2. The Technical Evolution of Soilless Cultivation Systems

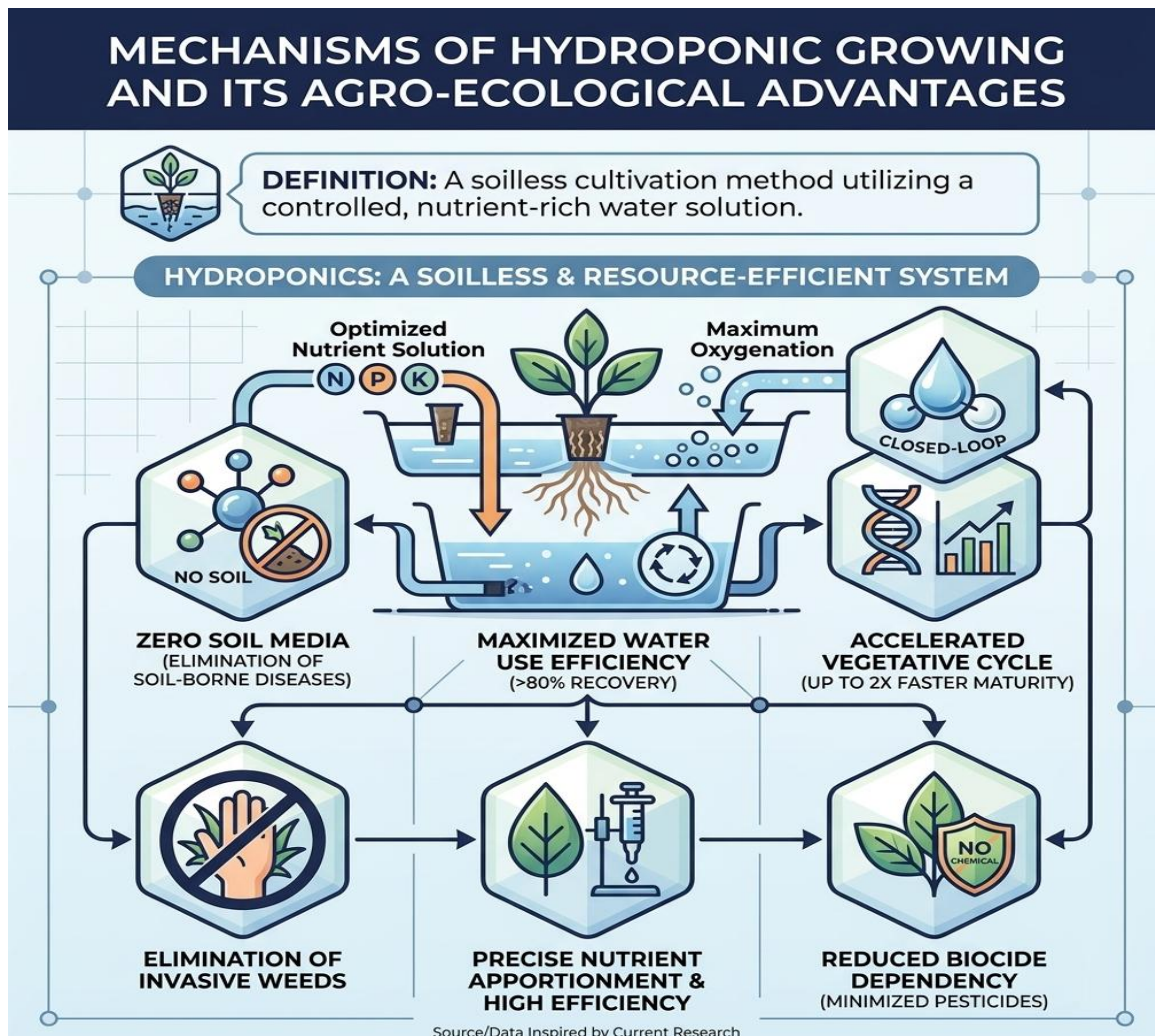
Soilless cultivation technology serves as the foundational architecture for modern vertical farming, providing the mechanism to bypass the biological and environmental limitations inherent in soil-based growth (Mahrous & Abd-Elkader, 2025). The primary objective is the delivery of essential nutrients directly to the root zone in a highly available form, eliminating the energy expenditure plants normally dedicate to root expansion (Kumar & Verma, 2024).

### 2.1 Hydroponic Dynamics and Substrate Innovation

Hydroponics, the most widely implemented soilless method, relies on mineral-enriched water solutions categorized into active and passive systems. The technical maturity of hydroponics has led to various configurations such as the Nutrient Film Technique (NFT) and Deep-Water Culture (DWC). Research identifies hydroponics as highly efficient, utilizing approximately 13 +/- 10 times less water than traditional methods (Salisu et al., 2024).

A significant trend in 2025 is the shift toward sustainable and environmentally friendly substrates to replace traditional rockwool. Researchers are focusing on agricultural waste-based substrates, such as coconut coir, peat blends, and bio-based foams (Yake Climate, 2025). The interaction between these substrates and rhizosphere microorganisms is a burgeoning field, where synthetic biology can enhance nutrient uptake and plant immunity (Tuxun et al., 2025).

Figure 2 Mechanistic Architecture and Agro-Ecological Benefits of Hydroponic Soilless Cultivation Systems



## 2.2 Aeroponics and the Optimization of Root Oxygenation

Aeroponics represents the cutting edge of soilless cultivation, suspending plant roots in an enclosed chamber and misting them with a nutrient-rich solution. This method eliminates the need for substrates, allowing for maximum root oxygenation (Farmonaut, 2026). Studies indicate that aeroponically grown plants can mature up to 25% faster and produce yields 20% to 45% higher than standard hydroponic setups. Furthermore, aeroponics is the most resource-efficient method, using up to 95% less water than traditional field farming (Kumar et al., 2024).

## 2.3 Aquaponics and Circular Nutrient Loops

Aquaponics integrates aquaculture with hydroponic plant cultivation in a symbiotic environment. In this closed-loop system, ammonia-rich waste from fish is converted by nitrifying bacteria into nitrates for plant nourishment (Bambhaniya et al., 2023). Case studies from the Netherlands have shown that high-precision aquaponic systems can achieve a 98% water recycling rate (Korea Journal of Agricultural Science, 2025).

**Table I: Comparative Analysis of Primary Soilless Cultivation Systems**

System	Water Delivery Method	Water Savings vs. Soil	Yield Index	Maintenance Complexity
Hydroponics	Continuous or periodic flow	70% – 90%	8x – 10x	Moderate
Aeroponics	High-pressure fine misting	95% – 98%	12x – 15x	High
Aquaponics	Fish waste nutrient cycling	90% – 98%	8x – 10x	Very High
Soil Farming	Manual/Automatic irrigation	0% (Baseline)	1x (Baseline)	Low to Moderate

### 3. Engineering the Vertical Farm: Architectural and Mechanical Integration

Vertical farming utilizes stacked layers within a Controlled Environment Agriculture (CEA) framework to maximize productivity per square meter. This paradigm is transformative for land-scarce cities, where one acre of vertical farming can yield produce equivalent to 10 to 350 acres of traditional farmland (Living Architecture Monitor, 2025).

#### 3.1 Lighting Spectra and Photosynthetic Optimization

Artificial lighting, primarily Light-Emitting Diodes (LEDs), is a necessity for stacked systems (PMC, 2025). Modern LEDs provide specific wavelengths primarily blue (400–500 nm) and red (600–700 nm) while minimizing energy waste. Recent innovations allow for spectral tuning, adjusting composition based on growth stages (Yake Climate, 2025).

#### 3.2 Architectural Integration in the Smart City

Agriculture is being integrated directly into urban architecture a concept known as Building-Integrated Agriculture (BIA) (Akintuyi, 2024).

- **Hybrid Facades:** Schools in Shenzhen and Shanghai have tested facades combining solar panels with vertical farming, reducing classroom glare by over 20% (Mahrous & Abd-Elkader, 2025).

- **Adaptive Reuse:** In Wuppertal, Germany, a former department store was redesigned as a vertical farm hub (Bonekämper, 2025).
- **Rooftop Greenhouses:** Integrated Rooftop Greenhouses (iRTG) leverage waste heat and CO<sub>2</sub> from the building below to fuel plant growth (Chen & You, 2024).

#### 4. Digitization and Autonomy: The Role of AI, IoT, and Robotics

The modern vertical farm functions as a data center. Machine learning and robotics handle the majority of operational tasks in what is becoming known as the "Autonomous, Epigenomic Farm" (Otekunrin, 2025).

##### 4.1 IoT Sensors and Robotics

IoT sensors monitor parameters such as pH, electrical conductivity (EC), CO<sub>2</sub> levels, and vapor pressure deficit (VPD) (HashStudioz, 2025). Robotics has advanced to sophisticated autonomous agents:

- **The Watney Robot:** Developed by Seasony, this robot automates transportation, reducing labor costs by 65% and increasing yields by 30% (GreyB, 2025).
- **LaserWeeder G2:** Carbon Robotics utilizes computer vision and lasers to identify and destroy weeds with millimeter precision (Carbon Robotics, 2025).
- **ARA Precision Sprayer:** Ecorobotix's ARA robot uses AI for plant-by-plant detection, reducing input use by up to 95% (Remus et al., 2024).

#### 5. Biotechnological Frontiers: CRISPR and Crop Diversification

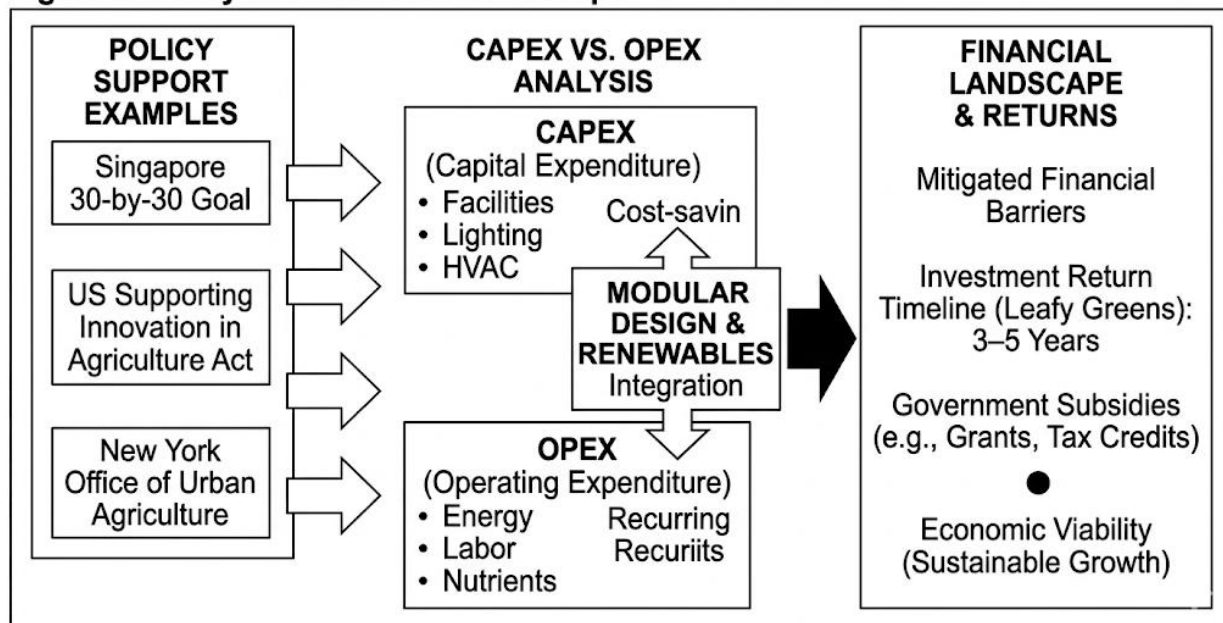
Advancements in gene editing are expanding the diversity of crops suitable for indoor production (Maximize Market Research, 2026).

1. **Rice Genetic Architecture:** Scientists have used CRISPR-Cas9 to target the SD1 and DEPI genes to create hyper-compact rice varieties. A truncated mutation of DEPI has been shown to simultaneously increase yield and resistance to sheath blight (Nagai et al., 2018).
2. **Vertical Wheat Success:** Wheat yields in vertical farms reached 8–10 kg/m<sup>2</sup> annually in 2025, compared to 2.6–3.5 kg/m<sup>2</sup> in traditional fields (Farmonaut, 2025).
3. **Specialized Micronutrients:** In-depth studies on Boron application in soilless mediums, such as coco peat, have shown significant improvements in the yield and quality of specialty vegetables (Singh et al., 2024).

## 6. Economic Realities and Policy Transformations

Despite technological sophistication, the industry faces rigorous economic landscapes characterized by high Capital Expenditure (CAPEX) and Operational Expenses (OPEX). Energy consumption for artificial lighting typically accounts for 50% to 65% of total electricity usage (PMC, 2025; International Journal of Plant & Soil Science, 2025). Economic and policy frameworks critically influence the adoption of vertical farming, summarized in Figure 7.

**Figure 2: Policy and Economic Landscape**



### 6.I Global Policy and Legislation

National governments are viewing vertical farming as a pillar of national security.

- **Singapore:** The revised "Singapore Food Story 2.0" targets 20% local consumption of fibre and 30% local consumption of protein by 2035 (Begum, 2025; Fu, 2025).
- **United States:** The proposed Supporting Innovation in Agriculture Act of 2025 (H.R. 1705) introduced by Representative Beyer aims to establish investment credits for innovative agricultural technology, including precision agriculture and CEA systems (Di Vaio & Ali, 2025).
- **New York:** The state is establishing an Office of Urban Agriculture to assist with and promote various forms of urban farming throughout the state (New York State Senate, 2025).

## 7. Conclusion

Vertical farming and soilless cultivation technologies offer a robust, scalable solution to urban food insecurity, decoupling production from traditional constraints and achieving unprecedented efficiency in resource use and output. By leveraging hydroponic/aeroponic/aquaponic systems with digital precision (AI sensors, optimized LEDs), these approaches not only mitigate climate and land degradation risks but also reduce environmental impacts through localized, pesticide-free operations. Despite barriers such as energy intensity and upfront investments, ongoing innovations in renewables, modular infrastructure, and microbial enhancements position them as economically viable for global megacities. Ultimately, widespread adoption could transform agriculture into a sustainable urban industry, ensuring nutritional equity and resilience in a resource-scarce future.

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