

# Vertical Farming As A Solution For Land Shortage In Cities

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**Abstract-** Rapid urbanization has placed tremendous pressure on available agricultural land, making it increasingly difficult to meet the food demands of growing city populations. Traditional farming methods require large tracts of land, which are simply unavailable in densely built urban environments. This paper examines vertical farming as a practical and sustainable solution to address land scarcity in cities. The study explores three core technologies—hydroponics, aeroponics, and aquaponics—and evaluates their technical working principles, components, benefits, and limitations. A comparative analysis of global case studies from Singapore, Japan, the United States, the Netherlands, and the UAE has been conducted. The methodology relies on secondary data gathered from published research papers, FAO reports, and government agriculture studies. Results indicate that vertical farming can reduce water usage by up to 95% compared to conventional agriculture, increase crop yield per unit area by 5 to 10 times, and enable year-round production independent of weather conditions. While challenges such as high energy costs and initial capital investment remain, the technology shows significant feasibility as part of smart city planning. This paper concludes that with appropriate policy support and technological improvements, vertical farming can play a meaningful role in achieving urban food security.

**Keywords:** Vertical Farming; Hydroponics; Aeroponics; Aquaponics; Urban Agriculture; Smart Farming; Sustainable Agriculture; Land Shortage; Food Security.

## I. INTRODUCTION

Cities across the globe are witnessing a sharp and sustained rise in their populations. According to the United Nations, approximately 56% of the global population currently resides in urban areas, and this share is projected to rise to 68% by 2050 [1]. This urban migration has led to a rapid reduction in available agricultural land near cities, even as the demand for fresh food continues to increase. In India alone, urban areas are expanding into fertile farming regions, and it is

estimated that nearly 1.5 million hectares of agricultural land has been lost to urban sprawl over the past two decades [2].

Traditional open-field farming depends on large expanses of arable land, seasonal weather patterns, and significant water resources—conditions that are increasingly difficult to satisfy in urban settings. Climate change has further complicated the situation by causing unpredictable rainfall, drought, and temperature extremes that affect crop yields. In countries like Japan, Singapore, and the Netherlands, where land availability is already critically limited, the need for alternative farming approaches has become urgent.

Vertical farming is an approach that grows crops in stacked horizontal layers within controlled indoor environments such as warehouses, shipping containers, or purpose-built structures. It integrates technologies like hydroponics, aeroponics, aquaponics, LED lighting, climate control systems, and IoT-based monitoring to create optimal growing conditions year-round. Because these systems operate independently of weather and geography, vertical farms can be located inside cities, reducing the need to transport produce over long distances.

The concept was first proposed in its modern form by Dr. Dickson Despommier of Columbia University in 1999 [3]. Since then, significant advances in LED technology, water recirculation systems, and automation have made commercial vertical farming increasingly viable. Companies like AeroFarms in the US, Sky Greens in Singapore, and Spread Co. in Japan have demonstrated that vertical farms can produce commercially significant quantities of leafy greens, herbs, and other crops profitably.

This paper aims to provide a structured analysis of vertical farming as a solution to urban land shortage, examining its core technologies, real-world applications, challenges, and potential for adoption in Indian cities.

## II. LITERATURE REVIEW

Research on vertical farming and related controlled-environment agriculture has expanded considerably over the past two decades. Dickson Despommier (2010) introduced the concept of the vertical farm in detail in his book 'The Vertical Farm: Feeding the World in the 21st Century,' arguing that multi-story buildings could serve as food production hubs for cities [3]. His work laid the foundation for subsequent commercial and academic exploration of the topic.

Benke and Tomkins (2017) conducted a comprehensive review of vertical farming prospects and concluded that while energy costs remain a significant barrier, advances in LED efficiency and renewable energy integration are progressively reducing operational expenses [4]. Their analysis highlighted that vertical farms are particularly suited for leafy greens and herbs but face challenges with larger crops.

Touliatos et al. (2016) compared hydroponic and soil-based cultivation systems and found that hydroponic lettuce yielded approximately 11 times more per square meter than traditionally grown equivalents, while using 13 times less water [5]. This finding reinforced the case for hydroponics as a viable urban farming method.

Lakkireddy et al. (2021) explored aeroponic systems for potato cultivation and reported that aeroponics produced 10 times more seed potato tubers per unit area compared to conventional field production [6]. Their study demonstrated the scalability of aeroponics for root and tuber crops beyond leafy vegetables.

Love et al. (2015) assessed the sustainability of aquaponics systems and found them to be efficient in water use—retaining over 99% of water compared to traditional agriculture—while providing dual outputs of vegetables and fish protein [7]. The researchers noted that aquaponics is particularly suited for communities with limited water access.

Al-Kodmany (2018) reviewed smart vertical farming technologies and emphasized the role of IoT sensors, automated nutrient delivery, and data analytics in optimizing crop growth [8]. His study documented several commercial vertical farms where automation reduced labor costs by up to 40%.

Benis and Ferrão (2017) examined the integration of urban agriculture in building design and concluded that rooftop and building-integrated vertical farms could supply between 2% and 15% of a city's vegetable needs depending on the city's density and building type [9].

Kozai (2013) analyzed plant factories with artificial lighting in Japan and noted that such facilities could produce lettuce at densities of up to 20 kg/m<sup>2</sup> per year, significantly exceeding field production rates [10]. Japanese plant factories have since become a global benchmark for vertical farming efficiency.

Banerjee and Adenaeuer (2014) reviewed the current state of vertical farming in Europe and noted that while the technology was still largely confined to demonstration projects, regulatory support and falling LED costs were beginning to attract commercial investment [11].

Cho et al. (2020) studied vertical farming adoption in South Korean urban centers and found that consumer willingness to pay a premium for locally grown, pesticide-free produce was a key driver of commercial viability [12]. Their findings suggest that market acceptance is a critical factor alongside technological readiness.

Taken together, the existing literature establishes that vertical farming is technically feasible and commercially viable under the right conditions, but faces challenges related to energy cost, crop variety limitations, and initial capital requirements. This paper builds on these findings by systematically comparing technologies and examining global case studies.

### III. TECHNOLOGIES USED IN VERTICAL FARMING

#### A. Hydroponics

Hydroponics is a soilless cultivation technique in which plant roots are directly exposed to a nutrient-rich water solution. Instead of extracting minerals from soil, plants receive a precisely measured blend of dissolved nutrients through water, which is recirculated through the system. The technique was formally studied as early as the 1930s by William F. Gericke at the University of California, who demonstrated large-scale tomato production using liquid nutrient solutions [5].

In a hydroponic system, plants are supported by an inert growing medium such as rockwool, perlite, coco coir, or clay pellets. The roots either sit in continuously flowing nutrient solution (as in the Nutrient Film Technique) or are periodically flooded and drained (Ebb and Flow). Other variants include Deep Water Culture (DWC), where roots are suspended in aerated nutrient water, and the Kratky method, which is a passive non-circulating approach.

Key components of a hydroponic system include the reservoir (water and nutrient storage), a pump, pipes or channels, a growing tray or panel, pH and EC (electrical conductivity) monitoring devices, and a timer. In indoor vertical farms, LED grow lights are also essential.

The main advantages of hydroponics are significantly faster plant growth (20–50% faster than soil growing), reduced water consumption (up to 90% less than conventional farming), no need for pesticides or herbicides, and the ability to grow in any location regardless of soil quality. Limitations include the high initial cost of infrastructure, continuous electricity requirement for pumps and lighting, and susceptibility to nutrient imbalances and disease spread through the water system.

Commercially, hydroponics is used widely for growing lettuce, spinach, basil, strawberries, and tomatoes. AeroFarms in New Jersey uses an advanced aeroponic variant, while Gotham Greens operates large rooftop hydroponic greenhouses in US cities. In India, companies like Barton Breeze and UrbanKisaan are developing hydroponic farms for urban markets.

### **B. Aeroponics**

Aeroponics is a more advanced soilless growing method in which plant roots are suspended in the air inside a closed chamber and are misted at regular intervals with a fine spray of nutrient solution. The technique was pioneered by NASA in the 1990s as part of research into growing food in space, where water and soil are impractical [6].

In an aeroponic setup, plants are held in place by a foam collar or net cup at the top of a chamber. High-pressure or low-pressure nozzles spray a nutrient mist onto the exposed roots every few seconds. Because roots are exposed to air rather than submerged in water, they receive abundant oxygen, which significantly accelerates growth and nutrient absorption.

An aeroponic system includes a high-pressure pump, misting nozzles, a closed growth chamber (typically opaque to prevent algae growth), timers, a nutrient reservoir, and monitoring sensors. High-pressure systems (80–100 PSI) create finer droplets (30–80 microns) and are more efficient for nutrient delivery than low-pressure systems.

Aeroponics uses approximately 95% less water than soil farming and 20% less than hydroponics, making it the most water-efficient vertical farming method. It also supports faster growth cycles and higher yields per unit area. The main disadvantages are higher equipment cost, technical

complexity, and the fact that even a brief pump failure can damage or kill crops due to root dehydration.

Aeroponics has found significant commercial application in seed potato production. BejoZaden in the Netherlands uses aeroponic mini-tuber production to generate certified disease-free seed potatoes with a 10x improvement in yield per unit area. In Singapore, ComCrop operates aeroponic vertical farms producing leafy greens for local supermarkets.

### **C. Aquaponics**

Aquaponics combines aquaculture (fish farming) and hydroponics in a single closed-loop ecosystem. Fish are raised in tanks, and their waste-laden water is pumped to plant grow beds. Beneficial bacteria convert ammonia from fish waste first into nitrites and then into nitrates—nutrients that plants readily absorb. The water, now cleaned of excess nutrients, is returned to the fish tanks. This creates a self-sustaining cycle where fish and plants support each other.

The main components of an aquaponics system include the fish tank, a biofilter (or media bed where beneficial bacteria colonize), plant grow beds or raft beds, a water pump, aeration equipment (air pumps and diffusers), and monitoring instruments for temperature, pH, ammonia, nitrite, and nitrate levels.

Tilapia and catfish are the most commonly raised fish species in aquaponics due to their hardiness and tolerance of varying water conditions. Trout and salmon can also be used in cooler climates. On the plant side, leafy greens such as lettuce, kale, and spinach, as well as herbs like basil and mint, perform best in aquaponics systems.

Aquaponics uses up to 90% less water than traditional agriculture because water is continuously recirculated. It eliminates the need for chemical fertilizers since fish waste provides natural nutrients. The system also produces two food products—vegetables and fish—from a single facility. However, managing the biological balance of the system is complex; fluctuations in fish population, feeding rates, or bacterial activity can upset nutrient levels and harm both plants and fish. Energy costs for pumping and aeration are also ongoing operational expenses.

## **IV. PROBLEMS AND SOLUTIONS**

Despite its potential, vertical farming faces several practical challenges that need to be addressed for wider adoption.

**High Energy Consumption:** Indoor vertical farms rely heavily on artificial lighting, climate control (cooling and heating), and water circulation pumps. Studies estimate that lighting alone can account for 25–30% of total production costs in plant factories [4]. **Solution:** Transitioning to high-efficiency LED lights (which consume 40–60% less energy than earlier fluorescent systems), integrating solar panels or renewable energy sources, and designing buildings with natural light optimization can significantly reduce electricity costs.

**High Initial Setup Cost:** A commercial vertical farm with full automation and climate control can cost anywhere from ₹50 lakhs to several crores depending on scale. This is a major barrier for small-scale farmers and startups. **Solution:** Modular container farms, shared vertical farming spaces (agri-coworking models), and government subsidies for urban farming infrastructure can help reduce entry costs.

**Water Quality Management:** In hydroponics and aquaponics, pH imbalances, pathogen contamination, or nutrient lockout can quickly damage crops. **Solution:** Automated monitoring systems with IoT sensors can track water pH, electrical conductivity (EC), dissolved oxygen, and nutrient levels in real time, triggering automated adjustments before problems escalate.

**Nutrient Balancing:** Providing the correct concentration and ratio of macronutrients (nitrogen, phosphorus, potassium) and micronutrients is challenging, especially across different crop species. **Solution:** Computer-controlled nutrient dosing systems can automatically prepare and deliver precise nutrient solutions based on plant growth stage and sensor feedback.

**Limited Crop Variety:** Most vertical farms are currently limited to leafy greens, herbs, and some fruiting plants. Staple crops like wheat and rice are not yet commercially viable in vertical setups due to space and light requirements. **Solution:** Ongoing research into dwarf crop varieties and optimized light spectrum protocols is expanding the range of crops that can be grown vertically.

**Electricity Dependency:** Power outages or fluctuations can damage temperature-sensitive crops or aeroponic systems where even brief misting interruptions can harm roots. **Solution:** Backup generators, uninterruptible power supply (UPS) systems, and battery storage integrated with renewable energy can ensure continuity.

**Technical Skill Requirement:** Managing nutrient solutions, monitoring plant health, and maintaining complex

irrigation systems requires trained personnel. **Solution:** Automated control systems, user-friendly dashboards, and training programs for agricultural workers can bridge the skills gap.

## V. ADVANTAGES AND DISADVANTAGES

Vertical farming offers a range of benefits over traditional agriculture, but also comes with notable drawbacks. Table I presents a comparative overview.

**TABLE I. Comparison of Vertical Farming vs. Traditional Farming**

Parameter	Vertical Farming	Traditional Farming
Land Use	Very high density (crops grown in layers)	Large land areas required
Water Consumption	Up to 95% less water used	High water usage; dependent on rain/irrigation
Pesticide Use	Minimal to none in controlled indoor environment	Significant pesticide application typically required
Crop Yield	5–10x higher per unit area	Limited by season, weather, and soil quality
Weather Dependence	None – fully controlled environment	Highly dependent on climate and seasons
Year-round Production	Possible regardless of season	Seasonal; limited to growing season
Energy Cost	High – requires electricity for lighting and HVAC	Low – primarily solar energy (sunlight)
Initial Investment	High capital cost for setup	Lower setup cost for most crops
Transportation	Low – can be	High if farms

Cost	located near consumers	are distant from urban markets
Crop Variety	Mostly leafy greens, herbs, and some fruits	Wide variety including staple grains
Environmental Impact	Reduced runoff, no soil erosion	Risk of soil degradation and water pollution

## VI. GLOBAL SURVEY AND CASE STUDIES

### A. Singapore – Sky Greens

Singapore imports approximately 90% of its food, making local food production a national priority. Sky Greens, established in 2012, operates the world's first commercial hydraulic-driven vertical farm using a rotating system that moves plants through light and shadow cycles, reducing energy use by 40% compared to conventional indoor farms [13]. The farm produces over 500 kg of vegetables per day including Chinese cabbage and spinach, supplying local supermarkets.

### B. Japan – Spread Co. and Plant Factories

Japan has over 200 commercial plant factories (indoor vertical farms) in operation [10]. Spread Co., based in Kyoto, operates one of the world's largest fully automated vertical farms, the Techno Farm Keihanna, which produces 30,000 heads of lettuce per day. The facility uses a fully automated system for transplanting, harvesting, and packaging. Japan's government actively supports vertical farming through subsidies and research funding as part of its food security strategy.

### C. United States – AeroFarms and Bowery Farming

AeroFarms, headquartered in Newark, New Jersey, operates one of the world's largest indoor vertical farms in a converted steel mill. The company uses a proprietary aeroponic system with reusable cloth grow media and claims to produce crops using 95% less water and 390 times more productively per square foot than conventional field farming [14]. Bowery Farming, based in New York, uses AI-powered monitoring systems and supplies fresh produce to major US retailers including Whole Foods and Amazon Fresh.

### D. Netherlands – Wageningen University Research

The Netherlands, despite being a small country, is the world's second-largest agricultural exporter, partly due to advanced greenhouse and vertical farming technology. Wageningen University's research programs have developed optimized crop protocols for indoor farming and have provided data showing that Dutch greenhouse tomatoes yield up to 75 kg/m<sup>2</sup> per year compared to 6–8 kg/m<sup>2</sup> in field conditions [15]. The country's investment in precision agriculture and controlled environment farming is seen as a model for sustainable food production globally.

### E. UAE – Badia Farms

In a region where agricultural land is scarce and water resources are critically limited, the UAE has invested in vertical farming as a food security measure. Badia Farms in Dubai, established in 2017, is one of the Middle East's first commercial vertical farms, producing over 16 varieties of microgreens, herbs, and baby leaves. The farm uses hydroponic systems with 99% water recycling and no pesticides, catering primarily to high-end hotels and restaurants in Dubai [13].

## VII. METHODOLOGY

This paper is based on a secondary data research methodology. The study involved a systematic review of published academic literature, technical reports, government agriculture documents, and news articles related to vertical farming, hydroponics, aeroponics, and aquaponics. The following steps were followed:

**Literature Collection:** Research papers were sourced from databases including Google Scholar, ResearchGate, IEEE Xplore, and Elsevier ScienceDirect. FAO reports and USDA documents were also referenced for global food demand statistics. A total of over 30 sources were initially identified, of which 15 were selected for in-depth review based on relevance and credibility.

**Technology Analysis:** Each farming technology (hydroponics, aeroponics, and aquaponics) was analyzed based on working principle, components, efficiency parameters, energy requirements, and crop suitability. This analysis was carried out through a structured comparison of findings from multiple sources to identify consistent patterns and conflicting claims.

**Case Study Review:** Five global case studies were examined from Singapore, Japan, the USA, the Netherlands, and the UAE to understand practical implementation challenges and commercial outcomes. Data about production

volumes, energy use, water savings, and market integration was collected from company publications, research papers, and news reports.

**Feasibility Assessment:** Based on the collected data, a qualitative assessment of vertical farming feasibility in Indian cities was conducted, taking into account the availability of electricity infrastructure, skilled labor, consumer demand for urban-grown produce, and regulatory environment.

**Comparative Data Analysis:** Quantitative data from the literature—such as water savings percentages, yield per unit area, and energy consumption figures—was tabulated and compared to draw conclusions about the relative efficiency of different vertical farming approaches.

## VIII. RESULTS AND DISCUSSION

The analysis of literature and case studies yields several key findings about vertical farming's potential and limitations.

**Water Conservation:** Hydroponic systems use 70–90% less water than conventional irrigation-based farming. Aeroponic systems achieve even greater efficiency, with water savings of up to 95% [6]. This is particularly significant for water-scarce regions like the UAE, western India, and parts of sub-Saharan Africa. In an era of growing freshwater scarcity—the UN estimates that 40% of the world's population will face water stress by 2030—this level of efficiency makes vertical farming a strategically important technology.

**Space Efficiency and Yield:** Vertical farms can produce 5 to 10 times more food per unit area than open-field cultivation, and up to 100 times more in the case of some high-density lettuce operations [10]. In cities where land costs are prohibitive, this space efficiency is a major economic advantage.

**Year-Round Production:** Unlike seasonal open-field farming, vertical farms can operate 365 days a year with consistent, predictable yields. This is particularly valuable for fresh produce supply chains where market demand is continuous but seasonal supply is not.

**Urban Sustainability:** By locating farms within or near cities, transportation distances are reduced from hundreds of kilometres to a few kilometres, decreasing fuel consumption and post-harvest losses. A study by Benis and Ferrão estimated that city-integrated vertical farms could

reduce food-related transport emissions by up to 30% in dense urban areas [9].

**Feasibility in Indian Cities:** India's tier-1 cities face growing food import dependency and rising land costs. With increasing consumer awareness of food safety and organic produce, demand for locally grown, pesticide-free vegetables is rising. Several Indian startups such as UrbanKisaan (Hyderabad) and Barton Breeze (Mumbai) have launched commercial hydroponic farms targeting urban markets. The main barriers are electricity costs (India's grid power remains expensive for industrial users), awareness among farmers, and lack of tailored government support schemes. However, with the declining cost of LED technology and increasing corporate interest in sustainable supply chains, the medium-term outlook is promising.

**Energy Consumption:** This remains the most significant challenge. Studies indicate that energy accounts for 20–30% of operating costs in fully controlled vertical farms [4]. However, the integration of solar panels, wind energy, and high-efficiency LED systems is progressively reducing this burden. In regions with abundant solar irradiance—such as Rajasthan or Gujarat in India—solar-powered vertical farms are technically and economically feasible.

## IX. CONCLUSION

Vertical farming represents a viable and increasingly necessary approach to addressing the dual challenges of rapid urbanization and food security. By growing crops in controlled indoor environments using hydroponics, aeroponics, and aquaponics, vertical farms can produce fresh, pesticide-free food year-round while using a fraction of the water and land required by conventional agriculture.

The global case studies reviewed in this paper—from Sky Greens in Singapore to AeroFarms in the United States—demonstrate that commercial-scale vertical farming is technically proven and economically viable, particularly for high-value crops like leafy greens and herbs. While challenges related to energy costs and limited crop variety remain, ongoing improvements in LED efficiency, automation, and renewable energy integration are making vertical farming progressively more accessible and affordable.

For countries like India, which face significant pressure on agricultural land due to rapid urban expansion, vertical farming offers an opportunity to integrate food production into smart city planning. Government policies that provide subsidies for renewable energy use in urban farms, dedicated zoning for food production in urban areas, and

public awareness campaigns about locally grown produce could accelerate adoption.

Looking ahead, the convergence of vertical farming with smart city technologies—IoT monitoring, AI-driven crop management, and data-driven supply chain integration—opens up possibilities for fully automated urban food ecosystems. As these technologies mature and scale, vertical farming is likely to become an important component of sustainable, resilient urban food systems globally.

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