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Vertical farming: A climate-smart and sustainable agricultural system

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Abstract

The accelerating pace of urbanization, coupled with mounting pressures from land degradation, freshwater scarcity, and climate variability, necessitates a shift in the global food production paradigm. Vertical farming has emerged as a transformative and scalable alternative to conventional agriculture, offering high-efficiency, space-optimized, and climate-resilient food production through advanced soilless cultivation methods such as hydroponics, aeroponics, and aquaponics. This review paper critically examines the basics, technological advantages, and sustainability dimensions of vertical farming, with a focus on the role of extension in promoting vertical farming. Beyond its technical significance, the contribution of vertical farming encompasses achieving food security, generating employment for urban people, and modernizing agriculture, aligning with a sustainable agricultural production system. Despite this, the field faces precarious restraints, including substantial energy demands, limited crop variety, high capital investment, and evolving regulatory frameworks. Even though traditional farming systems remain indispensable for diverse large-scale crop production, vertical farming offers an alternative and advanced model capable of tackling key environmental, economic, and social challenges. The paper emphasizes the need for technological scalability, continued innovation, and policy integration to unlock the full potential of vertical farming as a climate-resilient and sustainable agricultural production system.

Keywords: Vertical farming, aquaponics, aeroponics, hydroponics, sustainable agriculture

1. Introduction

1.1 Background

Currently, Indian agriculture faces numerous challenges including land scarcity, water shortages, climate variability, and the imperative to sustainably feed an expanding global population. Achievement of food security through traditional farming methods has been exacerbated by limited availability and rising costs of arable land (Al-Kodmany, 2018) [1]. With time, cutting-edge techniques like vertical farming have surfaced, enabling cultivation in unusual locations like abandoned buildings, underground tunnels, and shipping containers (Stull *et al.*, 2021) [29]. Controlled environment system where light, humidity, nutrients and temperature are regulated can be reconditioned into a dynamic agricultural system (Benke & Tomkins, 2017) [5]. Vertical farming embodies a shift toward high-efficiency, space-saving food systems, enabling crop cultivation on vertically stacked layers rather than on expansive land plots, thus amplifying output per square meter (Kalantari *et al.*, 2017) [15]. With rapid urbanization, the need to provide food for all, embracing eco-friendly measures, and increasing productivity has lifted the status of vertical farming (O'Sullivan *et al.*, 2020; Touliatos *et al.*, 2016) [21, 32].

1.2 Objectives

The primary objective of this paper is to understand the basics of vertical farming and its potential as a climate-smart and sustainable agricultural production system. The article aims to:

1. Explore the concept of vertical farming and its edge over traditional farming systems
2. Understand the tools and technologies of vertical farming
3. Analyze the benefits that make vertical farming a sustainable practice
4. Identify the challenges and limitations faced by vertical farming
5. Scrutinize the extension perspective in vertical farming
6. Highlight future prospects in the field of vertical farming

2. Vertical farming: concept and overview

2.1 Understanding vertical farming

Within vertical farms, plants are provided with exacting quantities of light, nutrients, and environmental parameters, leading to accelerated growth rates and the potential for year-round cultivation (Mohapatra *et al.*, 2023) [20].

Vertical farming is a cutting-edge way to grow crops, stacking them in layers instead of spreading them out across vast fields. This approach is fantastic for making the most of limited space, especially in cities or areas where good farming land is scarce or declining (Despommier, 2010) [7]. By shifting cultivation indoors, vertical farms can produce crops under controlled environment agriculture (CEA) systems where everything from light to temperature to nutrients is carefully controlled, leading to more consistent and productive harvests.

One of the central features of vertical farming is that it doesn't require soil. This means fewer worries about pests and diseases that come from soil, and a much lower demand for artificial fertilizers and pesticides. The result is food that's not only safer but also grown in a way that's much kinder to our planet (O'Sullivan *et al*., 2020) [21]. Furthermore, vertical farms use significantly less water and land, and they can produce food all year round. This makes a huge difference for food security and helps us adapt to the challenges of climate change (Avgoustaki & Xydis, 2020) [2].

Fig 1: Vertical farming (Source - Verner *et al*., 2017) [34]

2.2 Traditional farming vs vertical farming

The concept of vertical farming has emerged in response to an array of pressing challenges that threaten global food security. These include diminishing arable land due to urbanization, soil degradation, water scarcity, and the unpredictable impacts of climate change, all compounded by the need to sustainably nourish a global population projected to surpass 9.7 billion by 2050 (Foley *et al*., 2011; Sahoo *et al*., 2023; FAO, 2017) [11, 26, 10]. This method significantly reduces the demand for vast open fields, which are frequently associated with deforestation, habitat destruction, and a reduction in biodiversity. These issues are responsible for roughly 80% of global deforestation. Vertical farming also prevents soil degradation by eliminating the need for arable land, particularly with hydroponic systems that enable soilless plant cultivation. This positions it as a more sustainable alternative to conventional farming practices.

Another significant advantage of vertical farming is its water conservation capabilities. While agriculture accounts for 70-80% of global freshwater consumption, vertical farms employ closed-loop hydroponic and aquaponic systems that recycle nearly all water, substantially minimizing water usage. Dehumidification systems further collect and reuse water lost through plant transpiration, thereby reducing evaporation and runoff (Irfan, 2023) [14]. Vertical farming contributes to environmental conservation by decreasing the carbon footprint, as it negates the necessity for heavy machinery like tractors, commonly used in traditional farming. The utilization of energy-efficient LED lighting and the integration of renewable energy sources such as solar panels also contribute to lower emissions (Birkby & NCAT, 2016) [6]. Additionally, certain crops cultivated in vertical farms can sequester carbon, enhancing the overall environmental benefits of the system (TM *et al*., 2023) [31]. The compact vertical design further facilitates high productivity on minimal land area, making it ideal for urban environments and regions with unfavourable agricultural conditions. As public awareness regarding food safety and the environmental impact of farming grows, vertical farming aligns with the increasing consumer demand for environmentally conscious and pesticide-free food production.

	Traditional	Greenhouse	Vertical farm
Growth cycle	70 days	40-50 days	20 days
Water consumption per crop	35 l	15 l	1.5 l
Number of crops per square meter	18	25	250-300
Crop cycles	Seasonal	Seasonal	All year
Pesticides / Herbicides	Often	Less often	None
Location	Open field	Open field	Anywhere
Post-harvest handling	High	Medium	Low

Fig 2: Benefits of vertical farming over other systems (Source- https://robohub.org/rising-need-for-nursery-indoor-and-vertical-farming/)

3. Technologies and techniques of vertical farming

Vertical farming can be practiced in many forms, but there are three most popular systems: aquaponics, aeroponics, and hydroponics. These techniques form the technological foundation of modern indoor vertical farming systems. The major attraction factor for these systems lies in the fact that all of them employ soilless cultivation techniques to provide plants with wholesome nourishment.

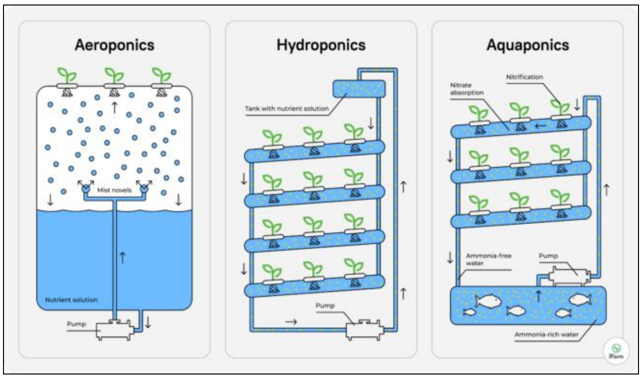

Fig 3: (Source: https://ifarm.fi/blog/vertical-farming-systems)

3.1 Hydroponics

The most common and popular farming system among the different types of vertical farming is hydroponics. This includes growing plants in nutrient-rich water without soil. Plant roots are immersed in nutrient-rich water solutions, which give essential minerals and nutrients directly to the roots. This approach uses less water and provides perfect control over nutrient delivery, resulting in faster growth and higher crop yields. This system is resistant to soil-borne diseases, pests, and insects (Manzocco *et al*., 2011) [19].

3.2 Aeroponics

In the 1990s, NASA (National Aeronautical and Space Administration, USA) sought to develop an effective method for growing plants in space, which inspired the popularisation of aeroponics. Aeroponics involves suspending plants in the air with their roots exposed. A nutrient solution, consisting of water and necessary minerals, is atomized into a thin mist or fog and administered directly to the roots. This strategy encourages quick growth and maximum output while saving water resources. This enables plants to absorb nutrients and oxygen more effectively than soil-based approaches, resulting in faster development and higher yields (Kumar *et al*., 2023) [16].

3.3 Aquaponics

Aquaponics is an innovative vertical farming approach that combines aquaculture with hydroponics to create a sustainable and symbiotic ecosystem. Aquaponic systems raise fish in tanks and turn their excrement into plant fertilizers. These plants filter the water, which is then recirculated back into the fish tanks. This closed-loop system maximizes resource efficiency, lowers waste, and produces fish and crops in a controlled environment, providing a sustainable food production option (Saini *et al*., 2025) [27].

4. Benefits of vertical farming

Vertical farming is widely recognized as an exceptionally efficient and sustainable food production method, particularly well-suited to the challenges of urbanization, climate change, and shrinking arable land. Unlike traditional agriculture, vertical farming allows for precise environmental control, resource conservation, and increased accessibility, thereby supporting food security and environmental resilience.

4.1 Maximized Yield per Unit Area

Vertical farming allows for multi-layered crop production, leading to significant yield increases compared to conventional horizontal farming. Research suggests that vertical farms can produce up to 40 times more food per square meter than traditional farms when optimized properly (Beacham *et al*., 2019; Al-Kodmany, 2018) [4, 1]. Crops grow faster in stacked systems with consistent lighting and climate control, making high-density production possible even in limited urban areas.

4.2 Reduced Resource Consumption (Water, Land, Pesticides)

Vertical farming significantly reduces water and chemical use through advanced soilless systems. Hydroponics uses up to 90-95% less water than traditional farming (Despommier, 2010; Graamans *et al*., 2018) [7, 12], while aeroponics is even more efficient, misting roots with minimal water. Controlled indoor environments also eliminate the need for pesticides and herbicides, lowering chemical runoff. The enclosed environment substantially reduces the risk of crop contamination from pollutants, pathogens, or heavy metals, resulting in produce that is not only fresher but also healthier for consumers (Al-Kodmany, 2018) [1]. When needed, farms often use biological controls like ladybugs to manage pests organically.

4.3 Urban Integration and Accessibility

Vertical farming integrates agriculture into urban settings, enabling cities to produce fresh food locally and reduce dependence on distant supply chains. Located in or near urban centres shortens the supply chain, reducing the time and distance between harvest and consumption. Thie "farm-to-table" approach ensures that fruits and vegetables reach consumers at peak freshness, flavour, and nutritional value. This approach cuts down on food miles and associated carbon emissions, while ensuring quicker access to nutrient-rich produce (Touliatos *et al*., 2016) [32]. By transforming vacant rooftops, abandoned warehouses, and unused commercial buildings into productive farms, vertical farming revitalizes underutilized urban infrastructure, enhances food security, and stimulates local economies.

4.4 Year-Round, Climate-Resilient Production

Vertical farming offers stable, year-round crop production by operating indoors, protected from climate extremes like droughts, floods, and frosts (Kalantari *et al*., 2017) [15]. This controlled environment allows for faster growth, multiple annual harvests, and consistent yields, regardless of external weather conditions—even in regions with poor agricultural climates (Banerjee & Adenaeuer, 2014) [3].

4.5 Improved Food Safety and Freshness

Vertical farming's controlled indoor environments minimize exposure to pathogens, pollutants, and soil-borne diseases, resulting in cleaner, safer produce. This not only enhances nutritional quality and taste but also significantly extends shelf life—leafy greens can stay fresh for up to 13-14 days, compared to just 3-4 days with traditional farming (Mohapatra *et al*., 2023) [20]. As a result, post-harvest losses and food waste are substantially reduced.

4.6 Energy Efficiency and Innovation

Modern vertical farms are increasingly adopting sustainable technologies like solar panels, wind energy, and energy-efficient LED lighting to reduce their environmental impact (Kozai, 2013; Benke & Tomkins, 2017) [, 5]. The integration of AI, IoT sensors, and automated climate control systems further enhances operational efficiency, allowing precise monitoring and resource optimization. As these technologies advance, energy consumption per unit of crop output continues to decline, making vertical farming more scalable and environmentally sustainable (Pant *et al*., 2022) [23].

4.7 Employment and Education Opportunities

Urban vertical farming is driving job creation across sectors such as agri-tech, engineering, data analytics, and urban logistics. These farms also act as centers for education and community engagement, raising awareness about sustainable agriculture and inspiring youth involvement and innovation in urban food systems (Despommier, 2010) [7].

5. Challenges and limitations of vertical farming

Vertical farming, while holding significant promise for revolutionizing agriculture, also faces some limitations that need to be addressed for widespread adoption and effectiveness.

5.1 High initial investment costs

One of the primary limitations of vertical farming is the substantial upfront investment required to set up the infrastructure and technology. Vertical farming facilities require specialized equipment, such as LED lighting systems, climate control mechanisms, and computerized watering systems, all of which incur significant financial costs (Panotra *et al*., 2024) [22]. Additionally, the cost of real estate in urban areas, where vertical farms are often situated, might drive up the initial investment.

5.2 Energy consumption

Vertical farming relies significantly on artificial lighting to augment or replace natural sunshine, especially in indoor environments. LED lights are widely utilized due to their energy efficiency; however, they still consume a significant amount of energy, resulting in higher operational expenses and an environmental impact. Moreover, maintaining optimal environmental conditions, including temperature, humidity, and CO2 levels, requires additional energy input (Lubna *et al*., 2022) [17].

5.3 Limited crop variety

Another challenge of vertical farming is the limited range of crops that can be effectively grown in vertical systems. While leafy greens, herbs, and certain fruits like strawberries thrive in vertical environments, tall field crops or crops with deep root systems may be impractical to cultivate. This limitation restricts the diversity of crops that vertical farms can offer compared to traditional outdoor farming (Lubna *et al*., 2022) [17].

5.4 Specialized knowledge and expertise

Vertical farming requires specialized knowledge in areas such as agronomy, mechanization, and controlled environment agriculture. Farmers must possess expertise in plant physiology, nutrient management, pest control, and data analytics to optimize crop growth and productivity. Acquiring and retaining skilled personnel can be challenging, particularly in regions where vertical farming is still emerging (Zeidler *et al*., 2017) [36].

5.5 Water Usage and Nutrient Management

Although vertical farming is often touted for its water efficiency compared to traditional agriculture, managing water usage and nutrient levels in hydroponic or aeroponic systems can be complex. Ensuring the proper balance of nutrients, pH levels, and water quality is essential for healthy plant growth and preventing nutrient deficiencies or toxicities (Sarkar & Majumder, 2015) [28]. Moreover, maintaining water purity and preventing contamination in recirculating systems requires meticulous monitoring and management.

5.6 Regulatory and policy considerations

The regulatory landscape surrounding vertical farming is still evolving, posing challenges for entrepreneurs and investors. Agriculture subsidies, building codes, zoning laws, and food safety requirements for traditional farming impact the feasibility and profitability of vertical farming ventures where these incentives are absent. Establishing vertical farming enterprises becomes more complicated and takes longer to get approved due to navigating these regulations (Al-Kodmany, 2018) [1].

In short, while vertical farming holds immense potential for sustainable food production in urban areas, it is not without its limitations. Addressing these challenges through technological innovation, research, and policy support will be crucial for unlocking the full benefits of vertical farming and realizing its role in the future of agriculture.

6. Future prospects for vertical farming

6.1 Advancements in technology and scalability

Technological and scalability advancements are critical to the future of vertical farming, as they can enable enterprises to overcome existing limitations and expand their reach. Vertical farming operations can enhance operational efficiency and optimize resource management utilizing ongoing innovation in fields like robotics, machine learning, and artificial intelligence (AI)-based control techniques such as machine learning (ML), deep learning (DL), the internet of things (IoT), image processing as well as computer vision can be a real game-changer (Rathor *et al*., 2024) [25]. Cutting-edge sensors and monitoring systems can offer data insights in real time, enabling proactive decision-making and improving crop output and health.

6.2 Integration into sustainable agriculture practices

Integration into sustainable agriculture practices is essential for vertical farming to realize its full potential as a solution to global food security challenges. Vertical farming operations can play a major role in minimising environmental impact and maximising resource efficiency. Vertical farming's potential to produce high-quality crops year-round in a controlled environment reduces reliance on conventional farming, which is vulnerable to climate change and environmental degradation.

6.3 Potential role in global food security
The potential contribution of vertical farming to global food security is its ability to diversify and enhance current food production systems, especially in areas confronting population expansion, water shortage, and land scarcity (Kalantari *et al*., 2018; Taher Abdelfatah & Mahmoud El-Arnaouty, 2023) [15, 30]. Vertical farming increases food resilience by offering a consistent supply of fresh produce regardless of weather or seasonality, minimizing the need for long-distance transportation.

7. Extension perspective in vertical farming
7.1 Knowledge and Awareness Status
Vertical farming, as a new agricultural approach, is relatively unknown to most conventional farmers, particularly in rural and peri-urban regions (Parameswari *et al*., 2024) [24]. In contrast, awareness is relatively higher among urban entrepreneurs, startups, and agritech firms, who see it as a modern solution to urban food demand, land scarcity, and consumer preferences for pesticide-free produce even though within these groups, understanding is often superficial and limited to basic concepts without a deeper understanding of system management, cost structures, or market linkages (Tyagi *et al*., 2024) [33]. Most countries' agricultural extension systems, including India's, have yet to incorporate vertical farming into their advisory services, with public agencies such as KVKs, State Agricultural Universities, and government departments promoting it sparingly (Mallick *et al*., 2023) [18].

7.2 Role of Agricultural Extension in Promoting Vertical Farming
Agricultural extension is a crucial driver in developing vertical farming by combining traditional and modern dissemination tactics. Farmers and urban entrepreneurs can gain knowledge about controlled-environment agricultural techniques such as hydroponics and aeroponics through practical approaches such as display units, field trips, and organized training programs. Modern ICT tools—mobile applications, digital advisory platforms, and animated video content—have increased the reach and accessibility of vertical agricultural information (FAO, 2021) [8]. Experiential learning techniques such as Farmer Field Schools (FFS) and participatory approaches promote hands-on understanding and group learning, particularly in urban and peri-urban areas (FAO, 2020) [9]. Collaboration between public agencies and private agritech startups through public-private partnerships allows for the scaling of knowledge dissemination and technical support through service-oriented models such as Vertical Farming as a Service (VFaaS) (ICAR, 2023) [13].

7.3 Capacity Building and Skill Development Needs
Vertical farming's effective adoption requires focused capacity building and skill development that is adapted to its technical complexity and resource constraints. Hydroponic and aeroponic systems, fertilizer management, temperature control, pest and disease monitoring, and post-harvest handling are all examples of specialized training modules (Parameswari *et al*., 2024) [24]. Krishi Vigyan Kendras (KVKs) and ICAR institutes play critical roles in developing and delivering practical workshops and short-term certificate programs, particularly for young people, agri-entrepreneurs, and farmers in urban areas (ICAR, 2023) [13]. These institutions can act as knowledge hubs by setting up model demonstration units and organizing exposure visits.

7.4 Challenges in Extension Delivery
One of the most significant problems in promoting vertical farming is its poor penetration in rural regions, where conventional farming techniques prevail and understanding of controlled-environment agriculture is limited (Parameswari *et al*., 2024) [24]. Vertical farming's high-tech character, which includes advanced climate control systems, nutrient management, and soilless production methods, serves as a substantial obstacle for small and marginal farmers, who frequently regard it as inaccessible or irrelevant to their settings.

7.5 Recommendations for Strengthening Extension Systems
To successfully promote vertical farming, policy-level interventions that formalize controlled-environment agriculture as a priority issue within national and state agricultural development policies are required. Vertical farming should be added to formal agricultural advisory services by developing dedicated training modules, incorporating it into KVK programs, and building extension personnel capacity to bridge existing knowledge gaps (Mallick *et al*., 2023) [18]. Revising agricultural curricula at colleges to include vertical farming technology will also help with long-term capacity development. Furthermore, involving startups and agritech enterprises as knowledge and service partners can greatly improve outreach and support for technical issues (FAO, 2021) [8]. These commercial companies may supplement public extension services with digital platforms, practical demonstrations, and tailored advising services by leveraging their innovative models (Tyagi *et al*., 2024) [33]. A public-private partnership (PPP) structure, backed by clear rules and incentive mechanisms, can effectively grow vertical farming adoption while making it accessible to both smallholders and urban enterprises (Parameswari *et al*., 2024) [24].

8. Conclusion
Vertical farming is an innovative system to grow food, basically stacking crops in layers inside buildings where everything is carefully controlled. It's brilliant for maximizing space, especially in cities where open land is scarce. Utilizing technologies like energy-efficient LED lights and soilless growing methods like hydroponics and aeroponics, these vertical farms can slash water usage by an impressive 90-95% compared to traditional farming. Additionally, because the environment is so clean and managed, they significantly cut down on, or even eliminate, the need for chemical pesticides.

Given the unpredictable nature of climate change and weather patterns, this approach offers a huge advantage: consistent, year-round crop production that isn't impacted by seasons or erratic weather. Vertical farming also helps shrink our carbon footprint by reducing the distance food has to travel, as produce can be grown right in the heart of urban areas, close to consumers. This not only means fresher, more nutritious food but also less waste.

From an economic and social perspective, vertical farming opens up new job opportunities in technology, agriculture, and urban planning. It also promotes sustainable urban development by transforming overlooked spaces like rooftops and old buildings into productive food-growing sites. All in all, vertical farming looks like a highly promising, adaptable, and sustainable answer to the world's growing food demands, while also tackling major environmental and resource issues that challenge conventional agriculture.

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