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Vertical hydroponic farming for indoor: A review

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Abstract

Vertical hydroponic farming is an innovative approach to agriculture that seeks to address the challenges posed by urbanization and the growing global population. This method leverages vertical space and hydroponic techniques to grow plants indoors, offering a sustainable alternative to traditional farming. This review paper explores the fundamental principles of vertical hydroponic farming, including the various hydroponic systems and vertical structures employed. It discusses the significant advantages of this farming method, such as space efficiency, controlled environment agriculture, water conservation, reduced pesticide use, and year-round production. The paper also addresses the challenges faced by vertical hydroponic farming, including high initial investment costs, energy consumption, the need for technical expertise, and the limited variety of crops currently suitable for hydroponic systems. The economic viability and environmental impact of vertical hydroponic farming are analyzed, considering factors like market demand, operational efficiency, and energy consumption. The future of vertical hydroponic farming, discussing the potential for expanding crop varieties, integrating renewable energy sources, supportive urban agriculture policies, and the importance of community engagement and education has also been discussed. This study aims to provide a comprehensive understanding of vertical hydroponic farming's current state, challenges, and future prospects, emphasizing its potential to revolutionize sustainable food production in urban environments.

Keywords: Vertical hydroponic farming, urban agriculture, sustainable food production

1. Introduction

Growing concerns about resource depletion, particularly land and water, are driving the need for innovative agricultural solutions. The UN predicts a population surge, reaching 8.6 billion by 2030 and 9.8 billion by 2050 (Khandaker and Kotzen, 2018) [1]. Factors like urbanization and unsustainable farming practices are shrinking arable land (Ramankutty *et al*., 2018) [2].This land conversion threatens food security (Nuryartono *et al*., 2017) [3]. Soilless agriculture, like vertical farming, emerges as a potential solution. Soilless farming offers greater control over growing conditions and reduces reliance on soil quality (Arcas-Pilz *et al*., 2021) [4]. Technological advancements and disruptions in traditional food supply chains further propel the rise of vertical farming (Lubna *et al*., 2022) [5]. This method addresses limited land availability, urbanization, and resource optimization.

Vertical hydroponics, a key component of vertical farming, offers significant benefits in India. Research shows improved resource efficiency in water usage, land use, and energy compared to traditional methods (Savitha *et al*., 2023) [6]. Ideal for urban environments, vertical hydroponics allows for efficient nutrient delivery through water, making it suitable for homes and enabling remote monitoring. Stacked growing systems maximize production in limited spaces, and hydroponically grown plants can be healthier due to a more balanced nutrient supply (Bugbee, 2003) [7] (Hayden, 2006) [8]. Vertical farming, with its eco-friendly and energy-saving nature, has the potential to feed a growing population and address resource limitations. It can play a crucial role in areas with limited soil and water, ensuring sustainable crop production (Mir *et al*., 2022) [9]. This review delves into the design, benefits, challenges, and future prospects of vertical farming for indoor use, with a specific focus on the Indian scenario.

2. Vertical farming

Vertical farming is a modern approach to agriculture where crops are grown indoors, stacked vertically. This method uses hydroponics or aeroponics (growing plants without soil) and offers several advantages. It maximizes space, uses less water, and reduces the need for pesticides and herbicides. Since it's indoors, it protects crops from harsh weather and allows year-round production. The concept of vertical farming was first proposed in the 1980s by a Swedish ecological farmer, with the idea of growing vegetables in urban areas (Despommier, 2013) [10]. Vertical farms can be set up almost anywhere, even underground, enabling local food production and delivering fresh, nutritious food throughout the year (Eldridge *et al*., 2020) [11] (Shamshiri *et al*., 2018) [12].

By using artificial lighting and climate control systems, vertical farming offers complete control over the growing environment. This allows for consistent yields of high-quality produce regardless of the season. Additionally, water recycling and nutrient recovery contribute to its efficiency and environmental benefits. Hydroponic systems are particularly well-suited for vertical farms, especially for growing fodder for livestock. Vertical farms can be incredibly productive, yielding up to 10 times more than traditional methods while using significantly less water (Khan *et al*., 2018) [13]. This makes them a promising solution for growing food in urban areas with limited space.

3. Role of vertical hydroponics in urban farming

A projected 40% population increase by 2050, reaching over 9 billion people (USDA, 2017), poses a significant challenge to global food security. Feeding this growing population necessitates a 70% rise in food production within the next 26 years (USDA, 2017), Land degradation further exacerbates this issue, requiring a potential 50-100% increase in food production per unit of existing land (Searchinger *et al*., 2018) [14]. Vertical farming presents a promising solution to this challenge. By leveraging controlled indoor environments, vertical farming mitigates societal, environmental, and economic threats to food security. Optimized conditions for temperature, humidity, CO_2, and lighting can significantly shorten growing cycles, increase plant density, and ultimately enhance (Khan *et al*., 2020) [15] (Treftz and Omaye, 2016) [16].

The benefits of vertical farming extend beyond increased production. This technology fosters eco-friendly and sustainable food production by reducing energy and water consumption, minimizing pollution, and improving access to fresh, nutritious food (Mir *et al*., 2022) [9]. Additionally, controlled environments shield crops from the detrimental effects of weather, pests, and contaminants often associated with traditional farming methods (USDA, 2017), Years of dedicated research have focused on perfecting various aspects of indoor farming, such as light intensity and spectrum, temperature regulation, CO_2 levels, and humidity control (Al-Kodmany, 2016) [17] (Harris, 1992) [18]. Interestingly, this technology also holds the potential to reconnect urban populations with nature through engagement in agricultural activities (Al-Kodmany, 2016) [17].

4. Essential Components of Vertical Farming Systems

Vertical farming leverages a combination of technologies and practices to cultivate crops in vertically stacked layers within a controlled indoor environment. This section explores the critical elements that contribute to the success of these systems:

4.1. Soilless Cultivation Techniques

Soilless farming methodologies form the bedrock of vertical agriculture in urban areas (Arcas-Pilz *et al*., 2021) [4]. These methods encompass diverse systems like Nutrient Film Technique (NFT), aeroponics, and drip irrigation, each offering distinct advantages suited to specific plant varieties and spatial limitations (Jensen, 2015) [19].

Hydroponics: The predominant approach in vertical farming, hydroponics cultivates plants with their roots submerged in a precisely formulated nutrient solution. Inert media such as rockwool or coir may be employed for root support (Jensen, 2015) [19]. This technique offers significant benefits, including increased yield per unit area and reduced water consumption.

Aeroponics: Plants thrive in a near-waterless environment with a precisely controlled mist of nutrient solution. This highly efficient system boasts lower water and fertilizer requirements compared to hydroponics. Research suggests aeroponics may also contribute to faster growth and potentially higher nutrient content in plants (Niam and Sucahyo, 2020) [20].

Fogponics: Representing an advancement in aeroponics, fogponics utilizes ultrasonic atomization to deliver an ultra-fine nutrient mist. This method offers superior energy efficiency and further reduces water and fertilizer usage compared to traditional hydroponics and aeroponics (Uddin and Suliaman, 2021) [21] (Banerjee 2022) [22].

Aquaponics: This sustainable and synergistic system integrates fish farming (aquaculture) with hydroponics. Nutrient-rich fish waste provides sustenance for the plants, while the plants filter the water for the fish, creating a closed-loop ecosystem. Minimal monitoring is required after initial setup (Samal *et al*., 2024) [23].

4.2. Artificial Lighting Systems

Due to limited access to natural sunlight, indoor vertical farms rely heavily on artificial lighting for plant growth. Light-Emitting Diodes (LEDs) are the primary source of illumination in these systems. The intensity and spectral composition of LED light significantly influence plant development and nutrient value (Pocock, 2015) [24] (Massa, 2008) [25]. Ongoing research focuses on optimizing LED light characteristics, including intensity, spectrum, and photoperiod, for various crops (Wong *et al*., 2020) [26].

4.3. Precise Nutrient Management

Optimizing plant growth necessitates meticulous management of nutrient solution composition and concentration. This involves maintaining a balanced blend of macro and micronutrients while ensuring proper pH levels (Resh, 2016) [27]. The nutrient solution must be biologically inert to prevent disease and malnutrition. Regular monitoring and adjustments of pH and electrical conductivity (EC) are crucial for ensuring optimal plant health (Mir *et al*., 2022) [9] (Kaur and Dewan, 2023) [28].

4.4. Selection of Growing Media

A variety of materials, such as coir, rockwool, and expanded clay, can serve as support structures for plants and mediums for nutrient delivery. Recent studies explore the impact of different growing media on factors like yield, water use efficiency, and overall plant health (Mahjoor *et al*., 2016) [29] (Wortman, 2015) [30] (Niu *et al*., 2015) [31].

4.5. Automation and Monitoring Systems

Incorporating automation for tasks such as nutrient delivery, lighting control, and environmental monitoring can significantly enhance the efficiency and manageability of vertical hydroponic systems. Sensor technology and the Internet of Things (IoT) enable real-time monitoring and adjustments, optimizing resource utilization and plant growth (Kacira, *et al*., 2020) [32].

5. Potential Benefits of Vertical Farming

Vertical farming emerges as a compelling solution for addressing challenges in agriculture and urban environments. Here's a breakdown of its key advantages:

Increased Crop Production: Vertical farming maximizes space by utilizing vertical structures, leading to significantly higher yields per square meter compared to traditional methods. This allows for more crops to be grown on a smaller footprint.

Year-Round Production: By creating controlled environments with artificial lighting, temperature regulation, and optimized nutrient delivery, vertical farms enable year-round crop production regardless of seasonal fluctuations or weather disruptions. This ensures a stable and reliable food supply.

Efficient Land Use: Unlike conventional agriculture requiring vast expanses of fertile land, vertical farming utilizes vertical space efficiently. This allows for higher crop densities and increased productivity on a smaller land footprint.

Reduced Water Consumption: Vertical farming systems often employ hydroponics or aeroponics, which can use up to 90% less water compared to traditional soil-based methods. Additionally, the captured water can often be recycled and reused, minimizing waste and overall water consumption.

Climate Resilience: Controlled environments in vertical farms offer protection from external climate factors such as droughts, floods, or heatwaves that disrupt traditional agriculture. This mitigates climate-related risks and contributes to stable, reliable food production even under changing climatic conditions.

Minimized Environmental Impact: Vertical farming has the potential to reduce the environmental footprint of agriculture. It eliminates the need for large-scale land clearing, reduces pesticide and herbicide use, and minimizes soil erosion. Additionally, controlled environments can mitigate pest and disease risks, lowering reliance on chemical interventions. Indoor cultivation also reduces or eliminates the need for heavy farm equipment, minimizing fossil fuel consumption.

Pesticide-Free Production: The controlled environments within vertical farms minimize pest threats, potentially eliminating the need for chemical pesticides. This ensures the production of cleaner, chemical-free crops. Some vertical farms may utilize biological controls like ladybugs for pest management.

Enhanced Control and Monitoring: Vertical farming systems offer a high degree of control over growing conditions. Real-time monitoring of environmental parameters (temperature, humidity, CO_2 levels, etc.) and plant growth metrics (fresh weight, shoot length, etc.) allows for data-driven decision making and continuous optimization of the farming process.

6. Challenges of Vertical Farming

While vertical farming offers exciting potential, it faces several hurdles to widespread commercial adoption:

High Startup Costs: Setting up a vertical farm requires substantial upfront investment in infrastructure, technology, and operational expenses like labour, energy, and supplies. (Kalantari *et al*., 2018) [33] (Patil *et al*., 2019) [34]. Temperature and humidity control, often through air conditioning, add significantly to operational costs (Specht *et al*., 2014) [35].

Energy Consumption: Indoor vertical farms rely heavily on artificial lighting and environmental controls, leading to high energy demands that can negate some of the sustainability benefits (Vanthoor *et al*., 2012) [36]. Strategies like using energy-efficient LEDs, optimizing light spectrum for specific crops, and integrating renewable energy sources can help reduce energy costs (Avgoustaki and Xydis 2020) [37] (Kozai *et al*., 2019) [38].

Technical Expertise: Successfully operating a vertical farm requires knowledge of nutrient management, lighting requirements, and system maintenance (Hochmuth and Hochmuth, 2020) [39].

Water Quality Management: Maintaining optimal water quality is crucial to avoid issues like nutrient imbalances and disease outbreaks. This involves monitoring factors like pH, electrical conductivity, and microbial contamination (Rakocy *et al*., 2006) [40].

Lack of Data Sharing: The industry struggles with limited collaboration and data sharing between vertical farmers and researchers. This secrecy leads to companies repeating efforts without knowledge of existing innovations. Increased transparency in energy use, resource consumption, and growing strategies could significantly benefit the industry (Lubna *et al*., 2022) [5].

Limited Crop Diversity: Current vertical farming models focus on high-value, fast-growing crops with a small footprint, like lettuce and herbs. The high production costs make it impractical to grow staple crops like corn, wheat, or rice in these systems. Vertical farming is likely to remain focused on leafy greens, herbs, and some specialty fruits like strawberries and peppers (Lubna *et al*., 2022) [5].

System Vulnerability: Mechanical or electrical failures can disrupt vertical farms, potentially leading to significant crop losses if not addressed quickly. Regular maintenance and monitoring are essential to mitigate this risk (Khan *et al*., 2018) [41].

7. Future Prospects for Vertical Farming

Despite current challenges, vertical farming holds promise for the future:

Technological Advancements: Continued research and development in hydroponic technologies are expected to improve efficiency, reduce costs, and make systems easier to use. Advancements in automation, lighting, and nutrient delivery will be crucial (Valladares *et al*., 2019) [42].

Integration with Smart Homes: As smart home technology evolves, vertical hydroponic systems could be integrated with home automation systems, allowing for seamless control and monitoring. This could make indoor gardening more accessible and convenient for everyday consumers (Mkhize *et al*., 2017) [43].

Sustainable Practices: Vertical hydroponics aligns perfectly with the growing focus on sustainability. These systems reduce food miles and promote local food production, potentially benefiting from increased awareness and support for sustainable practices (FAO, 2013) [44].

Educational and Therapeutic Uses: Beyond food production, vertical hydroponic systems offer educational and therapeutic benefits. In educational settings, they can provide hands-on learning experiences about plant biology and sustainability. Additionally, these systems can be used therapeutically, offering a calming and rewarding activity (Soga *et al*., 2017) [45].

8. India Scenario of Vertical Farming

While still in its nascent stages, vertical farming presents a compelling solution for addressing future agricultural challenges in India. The hydroponics market, a key indicator of vertical farming potential, has grown significantly, reaching an estimated value of $13.9 million USD in 2020 (Meticulous Research), Compared to developed nations like China and Japan, India may be in the early stages of adoption, but the future is promising with an anticipated CAGR (Compound Annual Growth Rate) of 18%. Water scarcity poses a major threat to Indian agriculture, with traditional methods consuming a staggering 84% of available water resources. Vertical farming offers a transformative solution by dramatically reducing water consumption by up to 95%. This makes it a highly attractive option for a nation facing water stress.

Furthermore, India's rapidly urbanizing population (over 377 million according to the 2011 census) places immense pressure on major cities like Delhi and Mumbai to meet the demand for fresh produce. Vertical farming offers a solution by efficiently utilizing underutilized spaces, such as abandoned buildings and factories, to establish vertical farms. This not only increases local food production but also contributes to urban revitalization efforts. The space efficiency of vertical farming is another significant advantage. Estimates suggest a 30-story vertical farm could match the output of a staggering 2,400 acres of horizontal farmland (Samal *et al*., 2024) [23]. This drastic reduction in land usage makes vertical farming ideal for densely populated areas.

8.1 Factors Driving Growth

Rising Demand for Fresh Produce: Urbanization and a growing focus on healthy living are driving the demand for fresh, high-quality produce. Vertical farming allows for year-round cultivation of a variety of crops, even in areas with limited land or challenging climates (Times of India, 2020),

Water Scarcity Mitigation: Water scarcity is a critical issue in India. Vertical farming's minimal water consumption makes it a highly attractive and sustainable solution for water-stressed regions (Jagtap *et al*., 2022) [46].

Technological Advancements: Advancements in automation, lighting solutions, and nutrient management systems are constantly improving. This makes vertical farming more user-friendly and accessible for both home growers and large-scale commercial farms (Thakur, *et al*., 2020) [47].

8.2 The Vertical Farming Landscape in India

Several companies are already capitalizing on the potential of vertical farming in India. Notable players include Urban Kisaan, Living Food Company, Triton Foodworks, UGF (Urban Green Fate) Farms, Agricool India, Future Farms, and 365Dfarms Growing Greens. These companies focus on cultivating a variety of crops specifically for the domestic market, including turmeric, microgreens, lettuce, chard, and herbs (Samal *et al*., 2024) [23].

9. Conclusion

Vertical farming presents a paradigm shift in urban food production, offering a viable solution to address the challenges of food security in densely populated areas. While initial investment costs, technical knowledge requirements, and energy consumption remain areas for optimization, vertical hydroponic systems hold significant promise for both individual consumers and commercial applications. Their capacity for water conservation, maximized space utilization, and year-round cultivation renders them a highly attractive option for the future. Looking ahead, advancements in automation, self-regulating systems, and renewable energy integration hold the potential to further enhance the efficiency and sustainability of vertical farming. Additionally, the development of cost-effective and user-friendly systems can broaden accessibility for a wider range of home growers and small-scale farmers. It is important to recognize that vertical farming is not intended as a complete replacement for traditional agriculture, but rather as a complementary approach, offering solutions in areas facing resource limitations and fostering efficient land usage. The potential benefits of vertical farming are undeniable, including reduced water consumption, minimized reliance on pesticides, shortened food supply chains, and demonstrably improved crop quality. To navigate the challenges associated with high initial investment and operational complexity, fostering collaboration and knowledge sharing within the industry is critical. As these issues are addressed through technological innovation and a focus on operational efficiency, vertical farming has the potential to become a viable and economically sustainable solution for meeting the ever-growing global demand for fresh, local, and nutritious food. This revised version adopts a more formal and professional tone, eliminating colloquialisms and emphasizing the transformative potential of vertical farming. It highlights the strategic advantages of the technology, the importance of responsible resource management, and the collaborative approach necessary to ensure its long-term success.

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