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# Vertical farming and controlled environment agriculture

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## ABSTRACT

The increasing global population, rapid urbanization, and declining availability of fertile land have increased the pressure on traditional agricultural systems, thus raising concerns regarding long-term food security and environmental sustainability. In the current situation, agriculture is significantly challenged by climate change, water scarcity, soil degradation, and excessive dependence on chemical inputs, which reduces productivity. These have demanded the adoption of innovative and resource-efficient farming approaches.

Vertical farming and controlled environment agriculture (CEA) has emerged as advanced cultivation systems that enable crop production in vertically stacked layers under controlled environmental conditions, including light, temperature, humidity, and carbon dioxide. These systems use modern technologies such as hydroponics, aeroponics, aquaponics, artificial lighting, and automated monitoring to increase productivity and resource-use efficiency. Existing literature highlights that vertical farming can significantly increase yield per unit area, reduce water consumption, minimize pesticide use, and ensure annual production. Also, recent studies highlight the role of dynamic environmental control and smart monitoring systems in optimizing plant growth and reducing operational costs.

But with these advantages, several limitations like large-scale implementation, high initial investment, and technological complexity is recorded. Also, lack of crop varieties supporting indoor systems and adaptation of renewable energy remain challenges. This review aims to provide an analysis of vertical farming and CEA by synthesizing current research on technological advancements, plant physiological responses, and energy system efficiencies.

## KEY WORDS

Vertical farming; Controlled environment agriculture; Plant growth; Plant physiology; Automated monitoring

## ARTICLE HISTORY

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## Introduction

The global agricultural sector is currently undergoing a period of transformation due to rapid population growth, accelerating urbanization, and increasing environmental damage. The global population is projected to reach nearly 9.7 billion by 2050, leading to an estimated 60–70% increase in food demand. Simultaneously, the availability of fertile land is declining due to urban expansion, industrialization, and land degradation. Traditional agricultural systems, which majorly depend on climatic stability, fertile soil, and water resources, are unable to cope with declining factors [1]. Climate change further affects the situation by changing precipitation patterns, thus increasing extreme weather events such as droughts and floods, and negatively affect crop productivity and quality. In addition, agriculture also contributes to environmental degradation through excessive water use, greenhouse gas emissions, and dependency on chemical fertilizers and pesticides.

Water scarcity has emerged as a major barrier, with agriculture depending for approximately 70% of global freshwater reserves. Increasing competition for water among agricultural, industrial, and domestic sectors is expected to rise in the coming years. Moreover, the supply chains associated with traditional farming contribute to increasing carbon emissions, food loss, and reduced quality of produce, particularly in urban areas where access to fresh and nutritious food remains distributed [2]. These challenges highlight the urgent need for sustainable agricultural systems that can ensure consistent food production while reducing environmental impact.

Vertical farming and controlled environment agriculture (CEA) have emerged as promising alternatives capable of transforming modern food production systems. Vertical farming involves the cultivation of crops in vertically stacked layers within enclosed environments such as buildings, warehouses, or shipping containers. This approach is closely integrated with CEA, where environmental parameters like light intensity, temperature, humidity, carbon dioxide concentration, and nutrient supply are controlled to increase plant growth and productivity. Unlike traditional agriculture, vertical farming systems operate independently from external climatic conditions, ensuring annual production with consistent yield and quality [3].

Vertical farming has evolved significantly with technological advancements. Hydroponic systems have demonstrated the ability to reduce water consumption while enhancing crop yield. Aeroponic systems also improve resource efficiency by delivering nutrients in mist form, ensuring maximum oxygen availability to plant roots. Aquaponic systems integrate plant cultivation with aquaculture, creating a closed-loop system that enhances sustainability [4]. These systems are supported by advanced lighting technologies such as light-emitting diodes (LEDs), which allows control over light spectrum and intensity.

Unlike static conditions, environmental parameters, like light intensity and photoperiod can enhance photosynthetic efficiency, improve resource utilization, and reduce operational costs. For example, variations in light intensity

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aligned with fluctuations have been shown to reduce energy costs without negatively affecting plant biomass. Such studies highlight the potential of integrating plant physiology with technologies, including sensors, automation, and artificial intelligence, to create responsive and optimized cultivation systems. Also, vertical farming offers the potential for higher yields per unit area, with some cases exceeding traditional field agriculture.

Despite these advantages, vertical farming and CEA systems has limitations. One of the primary challenge is the high initial capital investment required for infrastructure, technology, and system setup. Operational costs are also substantially high, particularly due to the high energy demand associated with artificial lighting and climate control systems. Also, technology requires skilled labor and continuous monitoring. Crop diversity in vertical farming also remains restricted, with most systems focusing on high-value, fast-growing crops such as leafy greens, herbs, and microgreens [5]. Also, concerns related to economic feasibility, scalability, and long-term sustainability continue as challenges for widespread adaptation.

The objective of this review is to provide a critical analysis of vertical farming and CEA systems, focusing on principles, technological components, and impacts on plant growth and productivity. The review aims to examine recent advancements in hydroponic, aeroponic, and aquaponic systems, as well as innovations in environmental control, automation, and monitoring technologies [6,7]. By studying the current literature, this review highlights future research directions and strategies to enhance the efficiency, scalability, and environmental viability of vertical farming systems.

## Evolution of Vertical Farming

Vertical farming is an agricultural approach involving crops in vertically stacked layers within controlled environments. This system is based on the principle of maximizing productivity per unit area by utilizing vertical space rather than expanding horizontally. It uses controlled environment agriculture (CEA) techniques, where key environmental parameters such as light intensity, temperature, humidity, carbon dioxide concentration, and nutrient availability are regulated to increase plant growth. Unlike traditional soil-based farming, vertical farming commonly uses soilless cultivation systems such as hydroponics, aeroponics, and aquaponics, which allow efficient delivery of nutrients and water directly to plant roots. These systems reduce water consumption and eliminate dependency on natural soil conditions [8]. The ability to maintain stable and reproducible environmental conditions ensures consistent crop quality and enables year-round production.

The term "vertical farming" was first introduced in the early 20th century, but it gained prominence through the work of Dickson Despommier, who popularized the idea of cultivating crops in multi-story urban buildings. Early conceptual models presented large-scale indoor farms integrated within urban infrastructure. However, technological limitations initially affected their production [9]. With improvements in lighting systems, environmental control technologies, and hydroponic techniques, vertical farming began to develop from concept to application. The establishment of pilot systems, such as early experimental vertical farms in countries like Japan and Singapore, marked a significant milestone in its evolution.

## Controlled Environment Agriculture

Controlled Environment Agriculture (CEA) forms support system of vertical farming by using environmental conditions to improve plant growth and productivity. Major environmental parameters include light, temperature, carbon dioxide ($CO_2$) concentration, humidity, and airflow, which influence the plant physiological processes. The use of LED lighting allows farmers to control light spectra to improve photosynthesis, regulate plant morphology, and improve crop quality. Temperature plays a vital role in enzymatic activity and metabolic processes, while $CO_2$ enrichment improves photosynthetic rates and biomass accumulation. Humidity and airflow regulate transpiration, stomatal conductance, and nutrient uptake. Air circulation also influences boundary layer resistance and gas exchange efficiency [10]. The control of these parameters ensures consistent yield and quality despite external environmental variability. Variable lighting, particularly dynamic light intensity control, increases energy use without affecting plant growth. Studies indicate that distributing light intensity with fluctuating electricity reduces operational costs while maintaining the same daily carbon release and biomass production [11]. Additionally, plants shows diurnal variations in physiological processes such as photosynthesis and stomatal conductance, even under constant environmental conditions. The success rate of CEA depends on advanced monitoring and feedback mechanisms that uses real-time data recording and system optimization. Sensors are used to continuously monitor key parameters such as pH, electrical conductivity (EC), temperature, humidity, and $CO_2$ concentration, providing critical inputs into plant growth and system performance. These data are integrated with artificial intelligence (AI) and crop growth models to predict plant responses. Such systems allow for adaptive management, where environmental conditions are adjusted to maintain maximum growth conditions [12]. The integration of IoT-based technologies and smart agriculture platforms further enhances system efficiency by using remote monitoring, automation, and predictive decision-making.

## Technologies in Vertical Farming

### Hydroponics

Hydroponics is the most widely used cultivation technique in vertical farming, involving plant growth in nutrient-rich aqueous solutions without soil use. This method uses control over nutrient composition, pH, and water delivery, thereby increasing plant growth and productivity. Among the commonly used hydroponic techniques, the Nutrient Film Technique (NFT) involves a continuous flow of a thin nutrient solution over plant roots, ensuring efficient nutrient uptake and aeration [13,14]. Deep Water Culture (DWC) suspends plant roots in oxygenated nutrient solutions thus providing constant access to water and nutrients. Hydroponic systems are highly efficient in water use due to recirculation mechanisms, with studies proving water savings of up to 90% compared to conventional soil-based agriculture [15]. Also, hydroponics reduces the risk of soil-borne diseases and allows for high-density crop production.

### Aeroponics

Aeroponics is an advanced soilless cultivation technique in which plant roots are suspended in air and sprayed with mist of nutrient solution. This provides high oxygen availability to the roots, improving respiration and nutrient absorption, which can lead to faster plant growth and improved biomass accumulation. Aeroponics was initially developed by the National Aeronautics and Space Administration (NASA) as a potential method for growing plants in space, highlighting its efficiency and innovation. Compared to hydroponics, aeroponics uses even less water and nutrients, as the mist delivery system minimizes waste.



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## Aquaponics

Aquaponics integrates aquaculture with hydroponic plant cultivation in a symbiotic, closed-loop system. In this method, fish waste acts as natural source of nutrients for plants, while plants simultaneously filter and purify the water, which is then recirculated back to the fish tanks. This system reduces the need for synthetic fertilizers and improves sustainability by recycling nutrients within the system. Aquaponics is considered environmentally friendly due to their efficient use of water and reduced waste generation.

## Lighting systems

Lighting is a critical component of vertical farming, as it replaces natural sunlight in indoor systems. Light-emitting diodes (LEDs) are the mostly used lighting technology due to their high energy efficiency, long lifespan, and ability to provide specific light spectra. By adjusting light wavelengths, particularly red and blue spectra, farmers control photosynthesis, plant morphology, and secondary metabolite production [16,17]. LEDs also generate less heat compared to traditional lighting systems, thus reducing the need for cooling.

Table 1 presents different vertical farming techniques and respective crop yields around the world. Table 2 provides a comparative analysis between hydroponics, aquaponics and aeroponics. Table 3 provides a comparison of lighting systems in vertical farming.

**Table 1.** Different vertical farming systems around the world.

| Name | Location | Products | Technology |
|---|---|---|---|
| Vertical Harvest | USA | Strawberries, tomatoes, lettuce | Hydroponic and LED light |
| Sky Greens Farm | Singapore | Herbs and leafy vegetables | Hydroponics, natural & artificial light, fertilizer and irrigation automation |
| Plantlab VF | Holland | Corn, tomatoes, strawberries, cucumbers, beans | Hydroponics, artificial LED, aeroponics |
| Planned Vertical Farm | Sweden | Green leafy vegetables | Hydroponics, aeroponics, natural lighting |
| Green Sense Farms | Portage, Indiana (USA), Shenzhen (China) | Herbs and lettuces | Automated sensors for light, humidity, fertilizers |
| Plant VF | Chicago | Mushroom, bakery, artisanal brewery | Aquaponics, hydroponics, sun energy |
| Aero Farms | Newark | Herbs and lettuces | Artificial environment, LED light, sensors, no soil pesticide |
| Vertical Crop | Canada | Strawberries, leafy vegetables | Light, humidity, temperature, fertilizers, irrigation controlled by sensors |
| Brooklyn Grange | Brooklyn, New York, USA | Beans, carrots, radishes, herbs, tomatoes, beets, fennel | Glow lights, automated sensors for irrigation, light, humidity |
| NUVGE Plant Factory | Japan | Leafy vegetables | Hydroponics, LED light, automatic rack system |

**Table 2.** Advantages and disadvantages of hydroponics, aeroponics, and aquaponics.

| System | Advantages | Disadvantages |
|---|---|---|
| Vertical Harvest | Minimal water and nutrient use | High initial setup costs |
| | Excellent aeration for roots | Requires precise control and monitoring |
| | Reduced risk of plant diseases | Vulnerable to power outages |
| | Faster growth rates | Limited to certain crop types |
| Hydroponics | Efficient water and nutrient use | Requires specialized knowledge and equipment |
| | High crop yield | Dependence on electricity and pumps |
| | Precise control over nutrient delivery | Risk of waterborne diseases |
| | Suitable for a wide range of crops | Limited root space |
| Aquaponics | Sustainable and eco-friendly | Complex system design and management |
| | Nutrient-rich water from fish waste | Balancing nutrient levels for fish and plants |
| | Reduced need for fertilizers | Higher initial costs and maintenance |
| | Dual production of fish and crops | Limited fish species suitable for the system |



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**Table 3.** Comparison of lighting systems in vertical farming.

| Lighting System | Efficiency | Lifespan | Spectrum Control | Heat Emission |
|---|---|---|---|---|
| Fluorescent Lights | Moderate | Moderate | Limited | Moderate |
| High-Pressure Sodium (HPS) Lights | High | Long | Limited | High |
| Metal Halide (MH) Lights | High | Moderate | Limited | High |
| Light Emitting Diodes (LEDs) | Very High | Very Long | Excellent | Low |

## Plant Physiology in Controlled Environment

### Photosynthesis and light response

Physiological responses in CEA is controlled by light availability and its interaction with photosynthesis. Light use plays a critical role in determining biomass accumulation, as photosynthesis depends on light intensity, spectral quality, and duration of exposure. A key parameter is the daily light integral (DLI), which represents the total amount of photosynthetically active radiation received by plants over a 24-hour period. Studies present a positive correlation between DLI and plant biomass production, proving that higher cumulative light exposure generally improves growth [18]. However, beyond threshold, the efficiency of light utilization may decline due to physiological limitations. In controlled environments, increasing DLI through artificial lighting systems allows precise regulation of photosynthetic activity, ensuring consistent growth rates.

### Resource use efficiency

Controlled environment enhances resource-use efficiency by increasing water, nutrient, and energy utilization. Water use efficiency is improved through closed-loop systems such as hydroponics and aeroponics, where water is recirculated. Nutrient uptake is also more efficient due to the direct delivery of formulated nutrient solutions to plant roots, reducing wastage and environmental contamination. Also, controlled environments helps better synchronization between resource supply and plant demand, thus enhancing overall metabolic efficiency [19].

## Advantages of Vertical Farming

### Resource efficiency

Vertical farming systems present improvements in resource-use efficiency compared to traditional agriculture. Major advantage is the water conservation, as hydroponic and aeroponic systems follows the recirculation method, thus reducing consumption by up to 90–95% compared to traditional soil-based farming. Also, vertical farming increases land use efficiency by utilizing vertical space through stacked cultivation layers, allowing substantially higher production within a limited carbon footprint. By removing the soil dependency, vertical farming also eliminates issues related to soil degradation and erosion [20,21]. The use of precise nutrient delivery systems further minimizes resource wastage.

### Productivity and yield

Vertical farming improves crop productivity through controlled environmental conditions and multi-layer production systems. By stacking multiple layers of crops within a single structure, vertical farms produce high output per unit area compared to traditional farming methods. Studies have reported that yields in vertical farming systems can be up to 10–60 times higher than conventional field agriculture, depending on the crop and system design. This increase is due to continuous year-round production, elimination of seasonal barriers, and precise control of growth conditions such as light, temperature, and nutrient supply. Furthermore, the controlled environment reduces variability in crop performance, ensuring uniform quality and predictable harvest cycles [22]. The ability to increase photosynthetic efficiency and plant growth parameters also contributes to enhanced biomass accumulation and faster growth rates.

### Environmental benefits

The controlled indoor environment reduces the need for chemical pesticides and herbicides, causing safer and cleaner food production. Also, the localization of vertical farms within or near urban centers significantly reduces transportation, thereby lowering carbon emissions associated with food distribution. The reduced dependency on agricultural land also helps conserve natural ecosystems and biodiversity. Vertical farming systems can also be used with renewable energy sources and sustainable waste management practices [23].

## Challenges and Future Prospects

One of the primary challenges is the high initial capital investment required for infrastructure development, including building construction, climate control systems, LED lighting, and automation technologies. Also, capital costs and operational expenses remain high due to continuous energy consumption, maintenance, and system management. The cost of skilled labor and technological upgrades adds to the financial burden. Artificial lighting, particularly LED-based systems, consists for major proportion of total energy use, often ranging between 60–85% of overall electricity consumption. Additional energy is required for maintaining required temperature, humidity, and ventilation within controlled environments. This high energy demand raises concerns regarding environmental sustainability, when non-renewable energy sources are used [24,25]. The use of sensors, AI-based monitoring, and climate control systems, further increases system complexity. Also, failure in system components such as pumps, lighting, or sensors can lead to rapid crop loss due to the controlled and sensitive nature of the environment. Crop diversity in vertical farming systems is currently limited, with most commercial operations focusing on high-value, fast-growing crops such as leafy greens, herbs, and microgreens. The cultivation of staple crops such as cereals and root vegetables remains economically and technically challenging due to space, energy, and growth requirements [26].

The future of vertical farming is closely linked with artificial intelligence (AI) and smart agriculture technologies. AI-driven systems help predictive modeling of plant growth by analyzing



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real-time data from sensors monitoring environmental parameters such as light, temperature, humidity, and nutrient levels. These systems can optimize resource use, adjust environmental conditions, and improve decision-making processes. Automation further improves efficiency by reducing labor requirements and ensuring precise control over cultivation processes [27]. The integration of Internet of Things (IoT) platforms allows remote monitoring and management, making vertical farming systems more scalable and efficient.

## Conclusion

The review highlighted the growing importance of vertical farming and controlled environment agriculture (CEA) as alternatives to traditional agricultural systems. This study demonstrated that vertical farming offers substantial advantages in terms of resource-use efficiency, enhanced productivity, and environmental sustainability. The integration of precise environmental control, soilless cultivation, and advanced technologies help crop production with quality. The findings of this review justify the increasing scientific study in vertical farming to counter the limitations of traditional agriculture. However, the review also identifies limitations that must be addressed. High capital and operational costs, energy dependency, technical complexity, and limited crop diversity remain major challenges that restrict large-scale implementation. Future research should focus on the development of energy-efficient systems, particularly integration of renewable energy sources and optimization of lighting strategies. Additionally, breeding and genetic improvement of crop varieties specifically suited for controlled environments represent a crucial area for research. The application of artificial intelligence, machine learning, and predictive modeling can further enhance system automation, decision-making, and resource optimization. Expanding crop ranges and improving system scalability will also be essential. In conclusion, vertical farming and CEA hold immense potential to develop sustainable agriculture, but their success depends on continuous technological innovation, economic optimization, and targeted research efforts.

## Disclosure Statement

The authors declare that they have no competing interests.

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