



Advancing Physiological and Agronomical Insights in Vertical Farming

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INTRODUCTION

Rapid population growth, accelerating urbanisation, climate variability, and diminishing availability of arable land have placed unprecedented pressure on global food production systems. Conventional agriculture, which relies heavily on fertile land, predictable climatic conditions, and large volumes of water and agrochemical inputs, is increasingly challenged by land degradation, water scarcity, and environmental pollution. In parallel, urban expansion has increased the physical distance between food production zones and consumers, contributing to post-harvest losses, higher transportation emissions, and reduced food freshness. These constraints have intensified the search for innovative agricultural models capable of producing high-quality food in a sustainable, resilient, and resource-efficient manner.

Vertical farming has emerged as a transformative approach to agricultural production that addresses many of these challenges. It is a form of controlled environment agriculture in which crops are cultivated in vertically stacked layers within enclosed structures such as warehouses, shipping containers, or purpose-built facilities. Vertical farming systems rely on artificial lighting, precise climate control, and soilless cultivation techniques, including hydroponics, aeroponics, and aquaponics. By decoupling crop production from external environmental conditions, vertical farming enables year-round cultivation, consistent yields, and predictable quality regardless of seasonal or climatic fluctuations.

Beyond its spatial efficiency, vertical farming offers significant advantages in terms of resource use efficiency. Closed-loop irrigation systems drastically reduce water consumption compared to field-based agriculture, while the controlled environment minimises nutrient losses and eliminates runoff. The absence of soil reduces exposure to soil-borne pathogens and weeds, thereby lowering the dependence on chemical pesticides and herbicides. These features position vertical farming as a promising solution for sustainable urban food systems and food security in regions with limited arable land.

While early research and commercial development of vertical farming focused primarily on engineering design, lighting technology, and economic feasibility, there is growing recognition that the success of these systems ultimately depends on a thorough understanding of plant physiological and agronomical responses to indoor environments. Plants grown under artificial lighting and tightly controlled microclimates exhibit distinct physiological behaviours related to photosynthesis, morphology, nutrient uptake, and water relations that differ substantially from those observed under natural field conditions. Similarly, agronomical practices such as planting density, nutrient formulation, and harvest scheduling require adaptation to the unique conditions of vertical farming systems.

Advancing physiological and agronomical insights is therefore critical for optimising crop productivity, quality, and resource efficiency in vertical farming. Integrating knowledge from plant physiology, agronomy, environmental engineering, and data-driven management enables the development of crop-specific production strategies that maximise system performance. This article aims to synthesise current scientific understanding of these physiological and agronomical dimensions, highlighting key advancements, challenges, and opportunities that will shape the future of vertical farming as a sustainable agricultural paradigm.

Objectives of the Article

This article aims to provide a comprehensive synthesis of advancements in physiological and agronomical knowledge related to vertical farming by addressing the following objectives

1. To examine plant physiological responses to controlled lighting, nutrient regimes, and microclimatic conditions
2. To evaluate agronomical performance in terms of yield, quality, and resource efficiency
3. To identify optimisation strategies for improving productivity and sustainability
4. To discuss current limitations and future research directions in vertical farming

1. Vertical Farming Systems and Core Principles

1.1 Controlled Environment Agriculture

Vertical farming operates within the broader framework of controlled environment agriculture, where environmental factors such as temperature, humidity, carbon dioxide concentration, and light intensity are precisely regulated. The primary goal is to create optimal growth conditions that align with plant physiological requirements and maximise photosynthetic efficiency and biomass accumulation. Controlled environments also reduce exposure to pests and pathogens, thereby lowering the need for chemical pesticides and improving food safety. In vertical farming, crops are cultivated in vertically stacked layers under precisely regulated environmental conditions (Figure 1).

1.2 Key Components of Vertical Farming Systems

Component	Function in Vertical Farming
Artificial lighting systems	Provide tailored light intensity and spectral composition for photosynthesis.
Nutrient delivery systems	Supply balanced nutrients directly to plant roots through soilless methods.
Climate control units	Maintain optimal temperature, humidity, and air circulation.
Sensors and automation	Enable real-time monitoring and adjustment of environmental parameters.

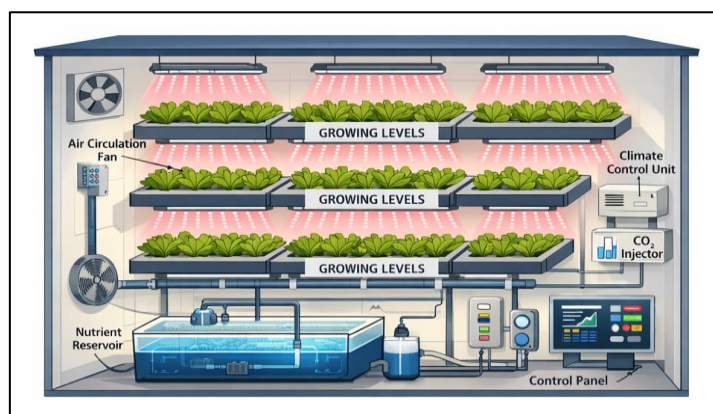


Figure 1. Schematic representation of a vertical farming system illustrating stacked crop layers, artificial LED lighting, hydroponic nutrient delivery, and environmental control components.

2. Plant Physiological Responses in Vertical Farming

2.1 Photosynthesis and Light Quality

Light is the most critical factor influencing plant growth in vertical farming systems since sunlight is replaced entirely by artificial sources. Light-emitting diode technology enables precise control over light intensity and spectral composition within the photosynthetically active radiation range. Light spectral composition strongly influences plant morphology and

photosynthetic performance in vertical farming systems (Figure 2).

Research indicates that red light is highly efficient in driving photosynthesis and biomass accumulation, while blue light plays a crucial role in stomatal regulation, leaf morphology, and photomorphogenesis. Additional wavelengths such as green and far-red light contribute to canopy penetration, shade response regulation, and biomass distribution.

Table 1: Effects of Light Spectrum on Plant Physiological Traits

Light wavelength	Primary physiological effect	Observed response in crops
Blue light	Stomatal control and leaf thickness	Improved nutritional quality and compact growth
Red light	Photosynthetic efficiency	Increased biomass production
Far red light	Shade response and elongation	Enhanced canopy expansion
Green light	Canopy penetration	Balanced morphological development

Optimal spectral combinations vary among crop species and developmental stages, highlighting the need for crop-specific lighting strategies.

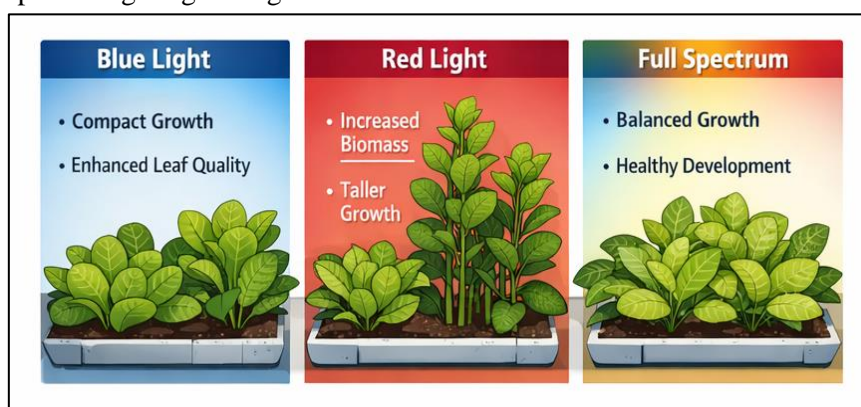


Figure 2. Influence of different LED light spectra on plant morphology and growth characteristics in vertical farming systems.

2.2 Nutrient Uptake and Root Physiology

In vertical farming systems, nutrients are supplied through precisely formulated solutions delivered directly to plant roots. This constant availability of nutrients alters root development and uptake dynamics compared with soil-based cultivation. Roots grown in hydroponic systems often exhibit increased nutrient absorption efficiency due to optimal oxygen availability and stable moisture conditions.

However, continuous nutrient exposure requires careful management to prevent nutrient imbalances or toxicities. Studies emphasise the importance of stage-specific nutrient formulations that adapt to changing plant demands throughout the growth cycle.

2.3 Water Relations and Microclimate Regulation

Controlled humidity and temperature directly influence plant transpiration rates and water use efficiency. Vertical farming systems typically achieve significantly higher water efficiency compared to conventional agriculture due to recirculation and reduced evaporation losses.

Nevertheless, excessive humidity without proper air circulation may increase the risk of physiological disorders and disease development. Therefore, precise microclimate regulation is essential for maintaining plant health and optimising water relations.

3. Agronomical Performance and Productivity

3.1 Crop Yield and Resource Efficiency

One of the primary advantages of vertical farming is the ability to achieve high productivity

per unit area. Multiple stacked layers enable continuous production cycles, particularly for leafy greens and herbs.

Studies report that crops such as lettuce can achieve annual yields exceeding sixty kilograms per square meter, which is

substantially higher than yields obtained under open field conditions. Water use efficiency in vertical farming systems can be several times greater than conventional agriculture due to closed-loop irrigation systems.

Table 2 Comparison of Productivity and Resource Use

Parameter	Vertical farming	Greenhouse cultivation	Open field cultivation
Lettuce yield per square meter per year	High	Moderate	Low
Water use efficiency	Very high	High	Low
Land use efficiency	Very high	Moderate	Low
Energy requirement	High	Moderate	Low

Despite these advantages, high energy consumption remains a major limitation affecting economic viability.

3.2 Economic and Environmental Considerations

Energy costs associated with artificial lighting and climate control represent the largest operational expense in vertical farming. In regions with high electricity prices, production costs may exceed those of conventional systems. However, when environmental externalities such as reduced water use, lower pesticide application, and decreased transportation emissions are considered, vertical farming offers significant sustainability benefits. Integrating renewable energy sources can further enhance environmental performance.

4. Optimisation Strategies in Vertical Farming

4.1 Precision Lighting Management

Adjusting light intensity and spectral composition according to crop type and growth stage can significantly improve productivity and quality. For example, higher red-light proportions during vegetative growth promote biomass accumulation, while increased blue light during later stages enhances leaf quality and nutrient content.

4.2 Advanced Nutrient Management

Real-time monitoring of nutrient solution composition allows for precise adjustments of nutrient concentrations in response to plant demand. This approach improves nutrient use efficiency and minimises waste discharge.

4.3 Automation and Decision Support Systems

The integration of sensor networks, internet-based monitoring, and artificial intelligence enables predictive control of environmental conditions. These systems can anticipate plant stress responses and adjust environmental parameters proactively, improving stability and reducing energy consumption.

4.4 Crop Specific Production Protocols

Different crops exhibit distinct physiological responses to various environmental factors, including light, nutrients, and temperature. Developing crop-specific protocols is essential for maximising productivity and expanding the range of crops suitable for vertical farming.

5. Challenges and Limitations

Despite its potential, vertical farming faces several challenges, including:

High energy consumption associated with artificial lighting
Limited economic feasibility for low-value staple crops
High initial investment and technical complexity
Need for skilled management and system maintenance
Addressing these challenges requires continued interdisciplinary research and technological innovation.

CONCLUSION

Advances in physiological and agronomical research have significantly enhanced the understanding of plant responses within vertical farming systems. Optimising light spectra, nutrient delivery, and microclimate control has demonstrated substantial improvements in yield, quality, and resource use efficiency. While energy demand and economic constraints remain critical challenges, ongoing developments in automation, renewable energy integration, and crop-specific management strategies are steadily improving system sustainability. Vertical farming represents a viable complement to conventional agriculture, particularly for urban food production and high-value crops.

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