



Resource Efficiency and Plant Productivity in Vertical Farming: A Comparative Analysis of Hydroponic and Aeroponic Systems

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Introduction

As environmental and geographical constraints continue to affect traditional agriculture, vertical farming offers an alternative solution for sustainable food production. Vertical farming is a controlled-environment agricultural practice that involves cultivating crops using hydroponic, aeroponic, or other soilless systems (Ling & Atland, 2025). This cultivation approach provides several advantages that are difficult to consistently achieve through traditional agricultural practices: first, the crops produced by traditional farming are limited by geography and seasonal changes; vertical indoor farming allows for the growth of regional and seasonal crops year-round, anywhere a controlled environment can be established (Ling & Atland, 2025). Second, vertical farming uses less land than traditional agriculture, as crops are grown indoors, often in vertically stacked layers, rather than horizontally across large fields (Ling & Atland, 2025). This method of farming allows for a greater crop yield per unit area. For example, a vertical farming greenhouse can produce 50–100 times greater yield per square foot than traditional agriculture due to its high-density, year-round production capacity (Funk, 2025). Third, vertically farmed crops can also often be grown without pesticides (Ling & Atland, 2025).

Among the most widely used soilless cultivation methods in vertical farming are hydroponic and aeroponic systems, both of which are designed to optimize resource delivery and plant productivity under controlled environmental conditions. Hydroponic systems utilize a nutrient-rich water solution as a root environment rather than soil, whereas aeroponic systems suspend plant roots in air and deliver nutrients through a fine nutrient-rich mist (Sihag et al., 2025). This paper evaluates how differences in water potential and nutrient delivery between hydroponic and aeroponic systems alter plant physiological processes, including photosynthetic efficiency, plant growth rate, and energy-use tradeoffs within vertical farming systems.

Principles of Plant Physiology

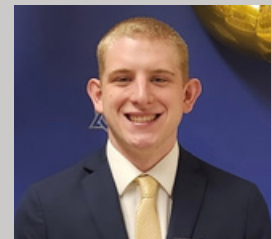
To understand these plant growth systems, we first need to understand the physiological mechanisms of plants that determine growth, productivity, and resource efficiency. A key process governing plant function is the movement of water, regulated by differences in water potential. Water potential refers to the free energy of water and determines the direction and flow rate of water movement within the soil–plant–atmosphere continuum (De Swaef et al., 2022). This movement is driven by gradients created through transpiration at the leaf surface, generating a pull of water through the plant (Trimble, 2022).

About the Authors



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I was born and raised in Leawood, Kansas, and came to the University of Missouri as a Biology major. Throughout college, I expanded my interest in health care through a variety of clinical and educational experiences and through my work in undergraduate research in neurophysiology. After graduation, I look forward to continuing my education through medical school and pursuing a career as a physician.



Cody Vondera

I was born and raised in Washington, Missouri. While attending Mizzou I pursued a degree in Biological Sciences and established a passion for dentistry. In my time at Mizzou, I enjoyed some new hobbies like running, camping, and hiking while also volunteering in the Big Brothers and Big Sisters program. After graduation, I plan to attend the UMKC Dental School.



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I was born in Illinois and raised in Columbia, Missouri. I am majoring in biological sciences and have always been fascinated with human anatomy. After graduation, I plan to apply to pathology assistant school and further my knowledge in anatomy and pathology. My goal is to get a master's degree and work in a medical examiner's office.

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Closely related to water movement is the transport of nutrients. The xylem transports water and dissolved ions from the roots upwards through the plant, while the phloem transports metabolites in solution to developing roots, leaves, and fruits (Lopez & Barclay, 2015). These processes ultimately support photosynthesis, the mechanism by which absorbed solar energy is converted into chemical bond energy in the form of carbohydrates (Johnson, 2016). The rate of photosynthesis is influenced by several environmental factors, including water availability, light intensity, carbon dioxide concentration, and temperature. The carbohydrate bond energy produced through photosynthesis is then used for growth, maintenance, and biomass accumulation (Weraduwege et al., 2015).

These physiological mechanisms lay the foundation of soilless agriculture systems used in vertical farming (Gurung et al., 2024). By monitoring and controlling water availability, nutrient concentrations, and environmental conditions, growers are able to directly influence plant functions at multiple levels to optimize growth conditions and resource-use efficiency, compared to traditional systems (Sihag et al., 2025). The ability to regulate these factors also reduces variability in plant production, allowing for more predictable outcomes in crop yield and quality (Gurung et al., 2024). These insights have led to the development of the modern systems seen in vertical agriculture today.

Hydroponics

Hydroponics, which means "water labor" in Greek, is an example of a soilless plant cultivation system commonly used in vertical farming (Gurung et al., 2024). This method relies on a nutrient-rich water solution to deliver essential ions directly to plant roots, eliminating the need for soil. Instead, plants are supported by inert growing media such as perlite, rockwool, or clay pellets, which provide structural stability while allowing the circulating solution to supply nutrients efficiently (Rajaseger et al., 2023). In these systems, water is continuously recirculated, maintaining adequate oxygen levels while delivering nutrients indirectly to the roots (Sihag et al., 2025). Hydroponic systems offer a range of advantages, particularly in optimizing resource use and spatial efficiency. One of the most significant benefits is water conservation, as hydroponic techniques have been shown to reduce water usage by up to 90% compared to traditional farming methods (Rajaseger et al., 2023). In addition to reducing water use, hydroponic systems have been shown to increase crop yields by approximately 20-25% compared to traditional soil-based agriculture, with some studies reporting even greater increases depending on crop type and growing conditions (Rajaseger et al., 2023; Sihag et al., 2025). Sihag and colleagues (2025) describe several additional benefits of hydroponic farming beyond water conservation and nutrient delivery. These include: improved pest control through controlled growing conditions, enhanced produce quality and flavor resulting from precise nutrient delivery, reduced water loss associated with evaporation and runoff through nutrient recirculation, and decreased exposure to soil-borne diseases and certain pest-related risks.

However, despite these benefits, hydroponic systems are not without challenges. Initial setup costs can be high, and many systems require intensive management, including frequent monitoring and maintenance (Rajaseger et al., 2023; Gurung et al., 2024). Although water is recirculated, hydroponic systems still utilize a moderate amount of water compared to newer technologies, which may present sustainability concerns (Sihag et al., 2025).

Aeroponics

Building on the principles of hydroponics, aeroponics has emerged as an innovative alternative designed to further enhance efficiency and resource conservation (Lakhia et al., 2024). While similar in concept to hydroponics, aeroponics eliminates the use of both soil and inert growing media, instead suspending plant roots in air and supplying nutrients through a fine mist. This system helps reduce plant stress factors such as hypoxia, salt accumulation in the root zone, and mechanical resistance that can hinder root development (Tafesse et al., 2021). Water mist rich in nutrients is delivered directly to the exposed roots through precision-controlled nozzles or sprayers, allowing for highly efficient nutrient delivery (Sihag et al., 2025). One of the most significant advantages of aeroponic systems is the increased oxygen availability to plant roots. Because roots are suspended in air rather than submerged in water, they are exposed to higher oxygen concentrations, which enhances cellular respiration and supports greater energy



production for growth (Tafesse et al., 2021). Another key strength of aeroponic systems is their ability to provide highly precise environmental regulation. In addition to maintaining consistent nutrient delivery, aeroponic systems allow for direct control of root-zone oxygen availability, pH, humidity, temperature, light exposure, and misting intervals (Gurung et al., 2024). This high level of control facilitates optimal growing conditions; improved oxygen availability and nutrient delivery in aeroponic systems can lead to enhanced plant growth and productivity compared to optimal hydroponic conditions (Tafesse et al., 2021; Sihag et al., 2025). This highlights a key tradeoff between systems, where hydroponics offers greater stability and scalability, while aeroponics prioritizes maximum resource efficiency and optimization of plant physiological performance (Sihag et al., 2025).

Compared to hydroponics, aeroponics uses significantly less water due to its misting and recycling mechanisms (Sihag et al., 2025; Lakhiar et al., 2024), while also providing greater oxygen exposure to plant roots. These factors not only accelerate plant growth, but also reduce disease susceptibility (Sihag et al., 2025), while maintaining the space efficiency necessary for vertical farming systems. In contrast, traditional soil-based and hydroponic systems are more susceptible to the spread of soil or water-borne pathogens, making the reduced disease transmission in aeroponics a key advantage for plant health (Sihag et al., 2025). Despite these advantages, aeroponics also presents notable challenges. First, the system relies on advanced technology that may make it more complex and potentially difficult for beginners to manage effectively. Second, the initial investment cost is typically higher than that of hydroponic systems due to the specialized equipment required for mist generation and environmental control (Sihag et al., 2025). When directly comparing hydroponic and aeroponic systems, aeroponics often demonstrates greater efficiency in water use, oxygen availability, and potential growth rates, while hydroponics remains more practical for large-scale implementation due to lower cost and system complexity (Sihag et al., 2025; Tafesse et al., 2021). This highlights an important tradeoff between maximum biological efficiency and real-world scalability, suggesting that the most effective system depends on the specific environmental and economic context.

Deployment of These Systems

Vertical hydroponic and aeroponic systems are frequently implemented in regions where traditional agricultural practices are limited or impractical due to environmental or geographic constraints (Ling & Atland, 2025). While several factors can contribute to suboptimal plant growth, traditional agricultural systems are often limited by seasonal variation in available sunlight. Each plant species has unique light requirements necessary for optimal growth and productivity (Mollick, 2025). Crops like tomatoes, peppers, and squash demand at least 6 hours of full-sun, while shade-tolerant leafy greens like kale and arugula manage with just three to four hours (Mollick, 2025). While these durations reflect the minimum light exposure necessary for plant growth, excessive exposure to full-sun conditions can also negatively affect growth in certain plant species. In addition to duration of light exposure, the light quality is also an important factor influencing optimal photosynthesis and plant growth. The quality of sunlight can be described by its spectrum (color) or wavelength of light, with different regions of the spectrum (wavelengths) producing different physiological effects within the plant. For instance, increasing the amount of blue light can result in more compact, stockier plants, while increasing red light intensity during flowering can enhance plant growth rates and crop yields (Don, 2025). Considering these two factors, exposure duration and spectral quality of the light, it's clear that traditional outdoor growing practices will not be equal in all places where sunlight serves as the sole light source.

LED Lighting in Vertical Farming

Vertical agriculture systems are not exempt from light conduction constraints, especially when located in indoor facilities that lack external light. To overcome these limitations and constraints, indoor facilities often incorporate light-emitting diodes (LEDs). Typical LED arrays used in vertical agriculture systems primarily supply photosynthetically active radiation (PAR) between 400 and 700 nm, which is optimally tuned to the absorptive properties of the plant photosynthetic machinery (Pereira & Gomes, 2025). Standard white-light LED bulbs have low PAR, limiting their ability to effectively support plant growth, while plants do not require all light wavelengths



produced by the sun, making specialized LEDs that produce optimal PAR more energy efficient (Savage, 2026). LEDs also contribute to the water-efficient goals associated with implementing hydroponic and aeroponic systems; specifically, how the plant moves and utilizes the water. The process by which plants absorb water through their roots, transport it upward through their vascular tissues, and release it as water vapor through their stomata is called transpiration (Helmenstine, 2026). In traditional agricultural systems, limited sunlight exposure can reduce stomatal activity, thereby slowing water uptake and transport within the plant (Park et al., 2023). LED use aims to optimize the stomatal opening time to promote growth. One study specifically studied the effects of far-red light (between 700-800 nm) on stomatal activity in sweet basil plants (Park et al., 2023). It was found that basil plants had a larger stomatal aperture area when grown with added far-red light and thus had greater evapotranspiration (combined process of water evaporation from the soil and transpiration through the plant) rates, leading to increased plant height (Park et al., 2023). This study exemplifies how LED lighting can have predictable and dramatic effects on plant growth when used with precision.

While LED lighting provides many benefits in these systems, it does not come without costs (Pereira & Gomes, 2025). Implementing these LED systems often requires elaborate technologies to have the desired effect. Specialized sensors and timing systems are required to fully utilize the adjustable spectral and intensity properties of LED arrays in order to optimize plant growth and agricultural productivity (Pereira & Gomes, 2025). Additionally, there is an inherent increase in energy use for vertical agriculture systems due to the equipment necessary to create these controlled environments. For example, the energy needs of lettuce grown using controlled environment hydroponics systems were more than 80 times greater than conventional methods (Pereira & Gomes, 2025). These increased energy requirements can contribute to substantially higher production and supply-chain costs. One economic comparison estimated the delivered cost of saleable lettuce at approximately \$7.82 per kilogram for vertically farmed lettuce, compared with \$3.04 per kilogram for conventionally field-grown lettuce (Gargaro et al., 2023). Although vertical farming may reduce transportation distances and provide more consistent year-round production, its dependence on artificial lighting and environmental control can therefore limit its economic competitiveness.

Conclusions

Vertical farming systems, particularly hydroponic and aeroponic systems, represent a significant advancement toward more controlled and resource-efficient food production under environmental and geographic limitations (Gurung et al., 2024). By leveraging plant physiological principles such as water potential, nutrient transport, and photosynthesis, these systems enable highly controlled growth conditions that improve resource-use efficiency compared to traditional agriculture (Gurung et al., 2024). While hydroponic systems provide reliable nutrient delivery and water conservation, aeroponic systems enhance root-zone oxygen availability and resource-use efficiency, often resulting in faster growth rates and increased productivity (Rajaseger et al., 2023; Sihag et al., 2025; Tafesse et al., 2021). The integration of advanced LED lighting systems further allows growers to precisely regulate light spectrum and duration in order to optimize plant performance (Pereira & Gomes, 2025). However, the benefits of these systems are accompanied by significant tradeoffs, particularly in terms of high energy consumption and technological complexity (Pereira & Gomes, 2025). Ultimately, the future of vertical farming depends on improving energy efficiency while maintaining high productivity. Continued innovation in lighting, system design, and environmental control will be necessary to achieve truly sustainable vertical agriculture.

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