Vertical farming and hydroponic production

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***Abstract*—Vertical farming integrates hydroponic crop production with vertically stacked cultivation layers, artificial lighting and controlled environmental management. Its principal change to hydroponic production is not simply the use of additional growing levels, but the coupling of nutrient delivery, lighting, air conditions, water management and crop handling within a compact production architecture. This paper synthesises evidence on the demonstrated capabilities and constraints of this architecture. It finds that vertical systems can increase control over the root-zone and aerial environment and can concentrate production within a limited footprint, but their outcomes cannot be inferred from stacking alone. Resource use, crop response and environmental performance depend on lighting design, climate-control demand, crop suitability, growing media, labour requirements, infrastructure and the energy context. Current sensing, dosing and automation systems demonstrate useful operational functions, whereas more integrated artificial intelligence and digital-twin approaches remain principally prototype-scale evidence. The paper concludes that vertical farming should be assessed through bounded system comparisons rather than universal claims of superiority. Future progress depends on validation across commercial operating conditions and on evaluation methods that connect crop performance with energy, lighting uniformity, nutrient control and operational reliability.**

I. Introduction

Vertical farming changes hydroponic production by arranging cultivation in stacked layers within a controlled environment, rather than by altering the basic principle of delivering water and nutrients without soil. The arrangement brings crop roots, nutrient solution, lighting, temperature, humidity and operational equipment into a more tightly coupled system. Hydroponic technologies can therefore support vertical arrangements, but the performance of a vertical farm depends on how those components are designed and managed together. Reviews of hydroponics identify controlled environments, resource management and associated technologies as connected system elements, not independent upgrades [1]. The important implication is that production density alone is not an adequate measure of performance, because greater spatial concentration can also increase the sensitivity of the system to energy demand, equipment reliability and management quality.

Soilless cultivation provides the production foundation for many vertical farms because it permits direct management of water, nutrients and the root environment. However, this potential does not establish a uniform advantage over other production systems. Comparative reviews assess yield, resource efficiency, nutrient management, substrate behaviour, cost and sustainability as related but distinct criteria [2]. A vertical hydroponic facility may improve control over selected inputs while introducing new requirements for infrastructure, lighting and technical operation. Consequently, claimed advantages should be expressed against a defined comparison basis, such as output per growing area, water use, nutrient efficiency or energy demand, rather than being treated as inherent attributes of all stacked systems.

The controlled setting also makes monitoring central to hydroponic production. Dissolved oxygen is an important example because its measurement and maintenance affect root-zone conditions, while available detection methods involve trade-offs in accuracy, stability and real-time response [3]. Advanced sensing and intelligent compensation are prospective directions, not automatic characteristics of operating vertical farms. This paper examines vertical farming as an integrated hydroponic architecture, explains the mechanisms through which stacking changes production decisions, and distinguishes demonstrated capabilities from projected performance. It then synthesises evidence on lighting, environmental control, resource comparisons and automation before considering the conditions that limit generalisation.

II. Background and Scope

Hydroponic production encompasses established equipment and operating practices alongside emerging proposals for smart control and digitally integrated management. Existing systems can use pumps, nutrient delivery equipment, sensors and environmental controls, whereas prospective Agriculture 4.0 approaches seek more extensive integration of data, automation and decision support [1]. This distinction matters when interpreting vertical farming claims. A facility can be vertically stacked and hydroponic without deploying advanced predictive control, and a demonstration of a sensing component does not establish whole-farm automation. The scope of vertical farming should therefore include the presently available production architecture while treating future digital capabilities as conditional developments that require separate validation.

Vertical farming belongs within a broader set of soilless agricultural systems that includes water-based cultivation, substrate culture and aeroponics. These approaches differ in how they support roots, circulate water, deliver nutrients and manage the crop environment. Reviews of urban and vertical systems identify resource control, crop compatibility, automation, energy requirements and adoption constraints as key differentiators [4]. Vertical stacking may increase the usable cultivation area within a building footprint, but it does not remove the need to select crops that suit the available light, root-zone configuration and handling process. A meaningful account of vertical farming must therefore connect the physical

arrangement of layers to the particular hydroponic or soilless method used on each layer.

The choice of growing medium can further alter system behaviour in vertical production. Reviews of soilless media compare air-water balance, water and nutrient efficiency, yield, cost, availability and environmental implications [5]. These factors are relevant where hydroponic cultivation uses substrate-supported plants rather than solely water-based channels or containers. A medium that supports root aeration may create different water retention, supply and disposal considerations from a recirculating water system. Thus, the scope of this paper is deliberately limited to the interaction of vertical arrangement and hydroponic production, with growing media treated as a design variable rather than as a universally beneficial or detrimental feature.

III. Core Concepts and Mechanisms

The root-zone method is one mechanism through which vertical farms can differ in production behaviour. Aeroponics, for example, delivers nutrient solution as droplets to exposed roots, while conventional hydroponics commonly maintains closer contact between roots and nutrient solution. Comparative work identifies potential performance differences as well as constraints associated with oxygen availability, temperature, aerosol behaviour, root exudates and system variability [6]. These constraints are significant in stacked facilities because a repeated layer design can reproduce both a successful root-zone condition and a recurring fault across multiple crop levels. Selecting a system therefore requires attention to controllability and fault response, not only to the theoretical intensity of root aeration.

Artificial lighting is another defining mechanism because stacked indoor layers cannot generally rely on direct sunlight to the same extent as unstacked or greenhouse production. Photosynthetically active radiation measurement is needed to determine what light reaches the crop, yet commercial sensors, lower-cost devices and remote approaches have different sources of error and practical applications [7]. Emerging sensor technologies may improve measurement capability, but they should not be assumed to resolve lighting design limitations by themselves. In vertical farming, light measurement supports decisions about distribution, intensity and crop response, while the value of those decisions still depends on the crop, fixture arrangement and the broader environmental-control strategy.

Integrated control links monitoring to operational action. A laboratory-scale hydroponic system has demonstrated sensing, nutrient prediction, fault recovery functions, model assessment and closed-loop control within a combined digital architecture [8]. Such work shows that hydroponic variables can be monitored and acted upon in a coordinated system, which is relevant to the repeated production zones of vertical farms. Nevertheless, measured sensor performance, model accuracy and response latency are bounded by the tested setting. The evidence supports prototype capability, not a general conclusion that complex vertical farms can reliably delegate operational decisions to automated systems under all commercial conditions.

IV. Evidence Synthesis

Lighting performance illustrates why vertical farming cannot be evaluated through stacking alone. Measurements of horticultural LED panels under plant-growth conditions show that photon efficacy depends on wavelength and colour temperature, while estimates of future efficacy remain projections beyond the tested configurations [9]. This distinction separates an observed property of particular lighting designs from a claim about future farm-wide energy performance. A vertical farm may use efficient fixtures, but its actual energy outcome also depends on how much light reaches plants, how fixtures are arranged, how heat is managed and how the lighting load interacts with climate control. Lighting assessment should therefore combine measured equipment performance with system-level operating conditions.

The distribution and spectrum of light are as consequential as the nominal output of a fixture. Work on indoor crop lighting shows that spatial photon irradiance and spectral variation can influence crop development and product value, and that a simple minimum-to-average measure may not fully represent lighting uniformity [10]. For stacked hydroponic production, this means that each layer should be evaluated at the crop canopy rather than assumed to receive equivalent conditions because it uses identical hardware. Measurement design, crop light response and spectral requirements shape whether a nominally uniform installation provides comparable productive conditions across the growing area.

Nutrient and water management also demonstrate the need to distinguish present evidence from future possibilities. Reviews of hydroponic food-production practices discuss current treatment and monitoring approaches alongside bioelectrochemical applications that remain early-stage and require scale-up and validation [11]. Such technologies may eventually contribute to resource-management strategies, but they do not presently justify broad claims about routine deployment in vertical farms. The stronger conclusion is that hydroponic systems offer defined points for monitoring and treatment, while the practical value of newer approaches depends on repeatable performance beyond experimental or proposed applications.

V. Practical Implications and Limitations

Comparisons between greenhouses and vertical farms require carefully bounded metrics. Reviews of controlled-environment agriculture compare energy, water, yield and emissions, while explicitly recognising that outcomes depend on energy source, climate and system design [12]. Vertical farms may concentrate production and allow close environmental control, but artificial lighting and indoor climate management can alter the energy profile relative to greenhouse production. Conversely, a comparison based only on energy can overlook water management, land use or crop-specific yield. Practical assessment should state the selected metric, the production boundary and the operating context before

concluding that one controlled-environment configuration is preferable to another.

The relationship between vertical farming and hydroponics is therefore architectural rather than synonymous. Hydroponics describes a family of soil-free nutrient-delivery methods, while vertical farming adds stacked space, infrastructure and controlled-environment arrangements. Reviews that compare hydroponics, aquaponics and vertical farming identify resource use, infrastructure, energy and nutrient management as linked design considerations [13]. This relationship clarifies why the advantages of vertical farming depend on system context. Crop choice, labour arrangements, capital requirements and operating energy are not secondary details: they influence whether the additional control and density translate into useful production outcomes for a particular facility.

Automation evidence should be interpreted with the same caution. An integrated hydroponic prototype has shown sensing, artificial intelligence, digital-twin synchronisation and control functions, but its authors identify the need for larger datasets, longer trials and external validation [8]. The result demonstrates a technical direction rather than commercial deployment. Similarly, automated pH sensing, calibration and acid dosing have been demonstrated in a greenhouse engineering test, although the reported benefits remain insufficiently quantified for broad commercial conclusions [14]. For vertical farms, the highest-value validation concerns sustained operation across multiple layers, variable crop conditions and realistic maintenance demands, rather than the successful operation of an isolated component.

VI. Conclusion

Vertical farming changes hydroponic production by combining soil-free cultivation with stacked growing space, artificial lighting and controlled environmental management. The evidence supports the value of this integration as a means of increasing spatial control and concentrating production, but it does not support treating stacking as an independent guarantee of superior resource, yield or environmental performance. Outcomes arise from interactions among hydroponic design, lighting quality, climate control, growing medium, crop suitability and operational reliability [2], [4], [13]. Assessment should therefore use explicit comparison metrics and defined system boundaries.

The most credible path to improved vertical hydroponic production is targeted validation of integrated operation. Lighting should be measured at crop level, nutrient and environmental controls should be assessed for reliability and fault recovery, and automation claims should be tested beyond prototype conditions [7], [8], [10]. Comparisons with greenhouse production must also retain the effects of energy source, climate and design context [12]. This evidence-based approach separates established operational capability from projected future performance and provides a more rigorous basis for evaluating vertical farming.

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