

Advanced Hydroponics Technology for Vegetable Production: New Opportunities and Challenges

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1. Introduction

In the new global era, the advancement of soilless cultivation technologies and the holistic “farm-to-table” approach to food production have become decisive factors for the sustainability and resilience of the agricultural sector [1]. Modern agriculture faces the unprecedented challenge of feeding a rapidly growing global population under the combined pressures of climate change, soil degradation, freshwater scarcity, and accelerated urbanization [2]. Within this scenario, Controlled Environment Agriculture and advanced hydroponic systems represent an essential paradigm shift toward sustainable intensification [3]. By decoupling crop production from the limitations of traditional soil, closed-loop hydroponic systems, vertical farms, and Plant Factories with Artificial Lighting (PFALs) offer precise control over environmental and nutritional variables, thereby maximizing crop yields, vegetables quality, and drastically reducing the ecological footprint [4].

This technological frontier opens unprecedented opportunities for modern olericulture, leveraging real-time phenotypic monitoring, smart automation, and the engineering of synthesized microclimates to optimize resource-use efficiency and enhance crop nutritional status [5]. However, the widespread scaling and economic viability of these advanced systems are often constrained by high capital expenditures and significant energy demands, particularly regarding artificial irradiance and climate regulation [6]. Furthermore, optimizing nutrient dynamics, understanding the precise morpho-physiological responses of horticultural crops, and elucidating nutrient uptake kinetics under synthesized conditions remain critical bottlenecks [7]. Addressing these challenges requires a deeper integration of data-driven agronomic protocols and circular nutrient solutions.

Consequently, this Special Issue aims to bridge these knowledge gaps by gathering cutting-edge research that addresses both the biophysical limitations and the techno-economic viability of modern soilless agricultural systems. Specifically, this volume focuses on elucidating the mechanisms for fully unlocking the potential of advanced hydroponics and paving the way for resilient and sustainable food systems. This volume contains six research articles, which we will briefly describe in the following paragraphs. In this regard, we clarify that the aim of this editorial is not to delve deeply into each of the texts, but rather to encourage the reader to explore them.

2. Contributions and Scientific Advances of the Special Issue

The research published in this edition addresses three fundamental pillars of modern hydroponics: the optimization of artificial lighting environments, the development



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of sustainable substrates based on the circular economy, and advanced plant nutrition management and foliar biostimulation.

In the first pillar, which focuses on the manipulation of the light spectrum and photoperiod, recent studies have reinforced the advantages of light-emitting diode (LED) technology over conventional high-pressure sodium (HPS) lamps in hydroponic production systems. Across several comparative studies, LED lighting consistently achieved yields comparable to or similar to those obtained under HPS while substantially reducing energy consumption and improving crop quality [8]. In hydroponic lettuce, LED systems required less than half the electricity consumed by HPS to produce plants of similar biomass, with two- to three-fold higher electrical efficacy. Moreover, lettuce cultivated under LEDs showed approximately 15% lower water consumption without compromising productivity [8]. In other hydroponic crops, such as tomato and cucumber, LEDs have also promoted improvements in early tomato yield and more compact plant architecture, including reduced stem elongation in lettuce while maintaining similar dry weight and leaf area [9]. These findings demonstrate that LED technology enhances resource-use efficiency and production sustainability, providing a strong foundation for its adoption in controlled-environment agriculture.

The article by Mirgos et al. (contribution 1) investigated the transition from traditional high-pressure sodium (HPS) lamps to light-emitting diode (LED) technology in the hydroponic cultivation of purple basil (*Ocimum basilicum* L.) using an NFT system. The authors demonstrated that a specific LED spectrum (deep red/blue) significantly optimized the plants' secondary metabolism, promoting a 31% reduction in leaf nitrate accumulation—a crucial advancement for food safety—while increasing levels of total sugars, vitamin C, chlorophyll *a*, and beta-carotene.

Expanding the boundaries of artificial light use in indoor environments, the study by Mir et al. (contribution 2) evaluated the combined effects of light intensity and different spectral blends on the growth, biomass accumulation, and energy use efficiency of various microgreen species. The results demonstrated that fine-tuning the blue-to-red light ratio dictates the system's energy conversion efficiency, enabling commercial producers to maximize dry matter production per kilowatt-hour consumed in vertical farms. These findings are consistent with those of Brazaitytė et al. [10], who demonstrated that adjustments to the blue-to-red light ratio significantly influence plant growth and nutrient accumulation in Brassicaceae microgreens, highlighting the importance of spectral composition for improving crop quality. More recently, Cowden et al. [11] further expanded this understanding by showing that, in addition to the light spectrum, fertilization management and planting density interact to influence biomass production and resource-use efficiency, emphasizing that optimizing indoor production systems requires an integrated approach combining lighting strategies with crop management practices.

Taking together, these studies demonstrate that spectral optimization is a key factor for productivity, nutritional quality, and energy efficiency in controlled-environment agriculture. Complementing this technological approach to lighting, Sant'Ana et al. article (contribution 3) explored an innovative synergy by combining light supplementation with the exogenous application of nicotinamide in tropical hydroponic green forage. Their findings indicated that integrating light with the application of this vitamin dynamically stimulates biometric parameters and accelerates the synthesis of photosynthetic pigments, offering a highly efficient methodology for producing high-nutritional-value forage within shortened operational cycles.

The second pillar of this edition addresses the search for eco-friendly substrates capable of replacing synthetic or non-biodegradable materials, such as rockwool. This research direction aligns with several recent studies demonstrating the need for more sustainable

materials in soilless cultivation. A hydroponic lettuce study identified grocery-waste compost as an excellent sustainable alternative and highlighted its contribution to a circular agro-food economy model [12]. Another lettuce substrate study emphasized that rockwool is not biodegradable, reinforcing the need to develop alternative substrates, particularly those derived from organic materials [12]. Similarly, coco fiber has been recognized as a promising organic substitute for mineral wool and perlite in soilless lettuce production [13], while coconut coir and carbonized rice husk have been shown to outperform rockwool for tomato cultivation under warm environmental conditions [14]. Together, these studies demonstrate that renewable organic substrates can simultaneously improve crop performance and reduce the environmental footprint of protected cultivation systems.

Responding to this demand for a circular economy, the article by Ju et al. (contribution 4) developed a new Molded Coconut Waste Substrate (MCCS)—stabilized with a hydrophilic polyurethane adhesive—designed for use in closed PFALs. By testing this material in the cultivation of lettuce and pak choi, the researchers successfully transformed an agro-industrial waste product into a high-performance bio-substrate. MCCS not only increased crop yields by up to 27.33% for lettuce and 67.19% for pak choi compared to traditional sponges but also reduced energy consumption per unit of production area by up to 40.91%, while compacting root architecture to facilitate automated mechanical transplanting.

The third pillar focuses on the chemical management of the nutrient solution and on strategic foliar interventions to mitigate abiotic stresses. Previous studies have consistently demonstrated the benefits of silicon supplementation in hydroponic systems. In hydroponic tomato, silicon was shown to prevent yield reductions commonly associated with increased electrical conductivity while simultaneously improving fruit firmness and vitamin C content. Silicon supplied through the nutrient solution also enhanced cuticle and epidermal thickness, strengthening the plants' natural defenses against pathogen pressure [15]. More recently, integrated nutrient management strategies combining potassium, calcium, and potassium silicate demonstrated that optimizing nutrient-solution chemistry together with foliar applications can improve plant growth, mineral nutrition, and fruit quality, highlighting the importance of chemical management as a key production strategy in hydroponic systems. Building upon this concept, the article by Baioui et al. (contribution 5) investigated the use of foliar silicon (1 mM Na₂SiO₃) applied weekly to tomatoes (*Solanum lycopersicum* L.) grown in a closed NFT hydroponic system. Silicon acted as a powerful physiological mitigator, increasing pigment concentration and the robustness of photosystems (PSI and PSII); this resulted in a significant 71% increase in total plant dry biomass and a 69% increase in marketable fruit yield.

Finally, the need to precisely calibrate macronutrient balances has become increasingly evident in hydroponic purslane production. Recent studies have demonstrated that optimizing nitrogen management is essential for simultaneously maximizing yield, nutritional quality, and resource-use efficiency. For instance, a hydroponic study recommended supplying 200 mg L⁻¹ N to increase the yield, nutritional value, and water-use efficiency of purslane [16]. Likewise, research evaluating the ammonium-to-total nitrogen ratio showed that plants grown with an Nr ratio of 0.05–0.10 exhibited lower oxidative stress together with greater water- and nutrient-use efficiency, with Nr = 0.05 identified as the optimal ratio for maximizing productivity and resource efficiency [17]. Earlier investigations into nitrate-to-ammonium balance also emphasized the importance of optimizing nitrogen forms to minimize oxalic acid accumulation in purslane leaves, reinforcing the value of balanced nutrient management. Collectively, these studies highlight a broader transition from conventional fertilization practices toward precisely calibrated macronutrient management in hydroponic systems. Building upon this concept, the article by Chrysargyris and Tzortzakis (contribution 6) mapped the exact nitrogen (N), phosphorus (P), and potassium

(K) requirements for hydroponically grown purslane (*Portulaca oleracea* L.). The study established optimal elemental ratios within the nutrient solution to unlock the vegetative and biochemical potential of this underutilized crop, balancing high productivity rates with increased water-use efficiency (WUE) and nutrient-use efficiency (NUE), while mitigating the environmental risks associated with over-fertilization.

3. Challenges and Future Perspectives

The body of research published in this Special Issue confirms that advanced hydroponics has established itself as a highly sophisticated biotechnological platform. However, transitioning these scientific discoveries to the large-scale commercial sector still presents significant challenges that the industry must overcome in the coming years:

3.1. Economic Viability and Capital Expenditure

The initial capital expenditure for implementing remains the primary barrier to the large-scale adoption of closed-loop hydroponic systems and vertical farms.

Bottleneck: Incorporating real-time nutritional monitoring sensors, AI-based automation systems, and LED arrays with dynamic spectra requires an investment that currently limits access for small and medium-sized producers.

Perspective: Future research should focus on “frugal innovation” and the democratization of technology. This entails developing low-cost sensors, open-source automated systems, and modular designs that allow for incremental scalability. Furthermore, long-term financial viability depends on expanding the crop portfolio: it is necessary to transition from niche, high-value crops (such as microgreens and leafy greens) to staple crops and agricultural commodities, thereby enabling global food security.

3.2. Overall Energy Efficiency

Although the use of circular substrates and organic spectral tuning, such as those proposed in this Special Issue, significantly reduces operating costs, the system’s total energy footprint, especially under artificial lighting and strict climate control, remains a subject of ecological debate.

Bottleneck: High reliance on the conventional power grid can, paradoxically, shift the environmental impact from the field (soil and water degradation) to the energy mix (carbon emissions).

Perspective: True sustainability for vertical farms requires an urgent decoupling from fossil fuels. The next scientific and engineering step involves the native integration of these systems with decentralized renewable energy sources (solar PV, wind, and biomass-based cogeneration) and the use of smart grids. Optimizing the thermodynamic modeling of the facilities to reduce the climate control load is just as vital as optimizing the photobiology of the plants themselves.

3.3. Nanotechnological and Physiological Mechanisms

As demonstrated by efficient responses to foliar applications and nutrient fine-tuning, the future of hydroponics lies in a molecular understanding of substance transport. The next scientific step requires deciphering how biostimulants and nanostructured fertilizers penetrate foliar cuticular barriers; this will enable further reductions in application rates and a move toward a zero-waste agricultural model.

Bottleneck: The empirical understanding of “how much” nutrients to apply must be replaced by a mechanistic understanding of “how” the plant absorbs and transports these nutrients under controlled conditions, minimizing stress and maximizing the assimilation rate.

Perspective: The frontier of hydroponics lies at the intersection with nanotechnology and molecular biology. The challenge for the coming years is to precisely decipher the kinetics of substance penetration through foliar cuticular barriers and root membrane transporters. The development of controlled-release nano-fertilizers and nano-encapsulated biostimulants will enable application rates to be reduced to minimal fractions, eliminating salt accumulation and paving the way for a truly closed-loop agricultural model with zero water and nutrient waste.

4. Conclusions

In summary, the articles comprising this Special Issue not only address immediate technical issues related to lighting, substrates, and plant nutrition, but also serve as a guide for future research in modern hydroponics technology for vegetable production. They demonstrate that the transition to resilient food systems with a low ecological footprint is not only urgent but also technologically feasible.

We extend our sincere thanks to the authors, whose cutting-edge research enriches this volume, and to the ad hoc reviewers, whose technical rigor ensured the scientific excellence of the published manuscripts. We invite readers, researchers, agronomists, decision-makers, and producers to explore the valuable findings presented in these six articles and to use them as a foundation for new innovations that will shape the future of global agriculture.

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