

4 Challenges and Future Perspectives

4.1 Technical and scientific bottlenecks

Despite rapid advances in artificial lighting, several technical and scientific constraints continue to limit the large-scale implementation of optimized spectral control in hydroponic systems. LED lighting, though markedly more efficient than conventional HPS or fluorescent systems, still entails substantial energy demands and high initial costs. The installation of LED arrays typically represents 40%-60% of the total setup cost, but payback can be achieved within 3-5 years due to reduced electricity consumption and extended lifespan (Patel, 2024).

In terms of energy performance, LEDs exhibit efficiencies of approximately 3.2-3.5 $\mu\text{mol/J}$, roughly double that of HPS systems, which range between 1.4-1.7 $\mu\text{mol/J}$ (Dannehl et al., 2021). Nonetheless, lighting remains one of the most energy-intensive components in commercial hydroponic systems, accounting for 25%-35% of total operational energy use. Although integrating AI-assisted dimming strategies can reduce this demand by 15%-20%, challenges persist in balancing spectral optimization with cost-effective implementation.

Another critical limitation lies in the complexity of spectral interactions. Light quality, intensity and photoperiod interact dynamically with temperature, humidity and nutrient status, making standardization across systems difficult. Discrepancies in experimental setups and reporting metrics also hinder the establishment of universal lighting “recipes” for specific crops, thereby restricting reproducibility and scalability.

4.2 Knowledge and research gaps

At the scientific level, our understanding of how specific wavelengths regulate plant metabolism and morphogenesis remains incomplete. While red and blue spectra are well studied, the physiological mechanisms triggered by green, far-red and ultraviolet radiation require further exploration. These spectral regions often display species-dependent and context-specific effects, complicating model development for precise spectral recommendations.

Integrating omics-based research can help fill these gaps. Transcriptomic and metabolomic studies, for instance, have revealed how light quality influences the expression of transcription factors such as HY5 and MYB, which control the biosynthesis of secondary metabolites and antioxidant pathways (Wu et al., 2023; Zeng et al., 2023). However, comprehensive multi-omics models linking light perception to metabolic regulation are still scarce (Zhang et al., 2022). Developing such integrative frameworks would enable predictive spectral modeling, advancing from empirical experimentation toward mechanism-driven control.

Artificial intelligence offers a promising avenue to accelerate the development of adaptive horticultural lighting systems. Machine learning and deep learning models have been successfully applied to predict light-response patterns and optimize spectral compositions, such as red-to-blue light ratios, in order to balance plant productivity with energy efficiency (Durmus, 2020). Recent developments integrate AI with real-time sensor inputs (including chlorophyll fluorescence, canopy temperature and CO₂ exchange) to create self-regulating lighting systems that adjust spectral outputs based on plant feedback (Srinivasan et al., 2024). Despite this progress, the lack of large, standardized datasets and benchmarks remains a critical limitation to fully validate and generalize these AI-driven systems across diverse crops and cultivation environments.

4.3 Future directions and integrated solutions

The next generation of hydroponic photobiology will depend on bridging molecular knowledge, intelligent technology and sustainable management. Integrating AI-powered lighting systems with sensor networks and cloud-based analytics can enable precision control, dynamic energy savings and data-driven decision-making. The convergence of omics research, machine learning and environmental monitoring represents a new paradigm for achieving both efficiency and resilience in crop production.

At the same time, economic and policy frameworks will be crucial to ensure accessibility and scalability. Initial investments in LED infrastructure remain a key barrier, particularly for small enterprises. However, global