

sustainability programs are increasingly providing financial and regulatory support. The European Green Deal (European Commission, 2020) includes incentive mechanisms for energy-efficient technologies and smart agriculture, while the FAO (2022) underscores the importance of digital agriculture and artificial intelligence in enabling “green transitions” within agri-food systems. Establishing standardized certification systems for energy performance, alongside public–private partnerships, will accelerate adoption and promote long-term economic viability.

Ultimately, the sustainable evolution of hydroponic lighting requires simultaneous progress in technological innovation, fundamental research and institutional collaboration. The integration of omics-driven understanding with intelligent control and supportive policy environments will define the next frontier in achieving productive, resilient, and environmentally responsible hydroponic systems.

5 Conclusion

In hydroponic agriculture, where environmental variables can be tightly controlled, artificial lighting emerges as a central factor not only for biomass accumulation but also for shaping plant morphology, metabolism and functional quality. This review demonstrates that light quality, intensity and photoperiod interact in complex ways with plant photoreceptors and metabolic networks, influencing growth performance, nutrient composition, and stress resilience.

Red and blue light remain the fundamental drivers of photosynthesis and photomorphogenesis, yet expanding the spectrum to include green, far-red and UV-A/B wavelengths provides new opportunities for fine-tuning physiological responses. Such spectral diversification enables both yield optimization and the enhancement of bioactive compounds, essential for the development of high-quality, functional crops.

Beyond physiological optimization, the integration of omics-based research and artificial intelligence offers a path toward precision photobiology. Multi-omics studies can clarify the regulatory mechanisms underlying spectral responses, while AI-driven control systems enable adaptive and energy-efficient lighting management. Together, these advances promise to transform hydroponic systems into intelligent, self-optimizing production environments capable of real-time response to plant needs.

However, technological innovation alone will not ensure sustainability. Future progress depends on coupling scientific and digital advances with supportive economic and policy frameworks. Coordinated global efforts that integrate research, industry and governance will be essential to accelerate the adoption of energy-efficient technologies, foster equitable access and enhance the resilience of agri-food systems.

In summary, overcoming the current technological and economic barriers in hydroponic photobiology will require bridging molecular-level understanding of light signaling with intelligent control and policy frameworks. The convergence of omics-driven research, AI-based spectral management and renewable energy integration represents the next frontier in achieving efficient, resilient and sustainable hydroponic production.

Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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