

## Light-Driven Nutritional Quality in Vegetable Protected Cultivation

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### Abstract

Environmental control is central to modern protected cultivation, yet among all growth factors, light is the most decisive driver of nutritional quality in vegetables. Here, we analyze how practical decisions about light intensity, duration (photoperiod), Daily Light Integral (DLI), and spectral composition influence the accumulation of vitamins, minerals, and secondary metabolites in greenhouse-grown vegetables. While temperature, CO<sub>2</sub>, and humidity also modulate growth, targeted manipulation of the light environment provides the most precise and energy-efficient lever to enhance produce quality. Specific wavelengths trigger photoreceptors—phytochromes, cryptochromes, phototropins, and UVR8—that regulate photosynthesis, redox status, source–sink allocation, and the biosynthesis of bioactive compounds such as carotenoids, flavonoids, anthocyanins, and phenolic acids.

From a practical standpoint, DLI and intensity set the baseline for photosynthetic carbon supply and antioxidant capacity: raising DLI within crop-specific optima increases vitamin C and phenolics, whereas supra-optimal intensities risk photoinhibition and quality loss. Spectral quality then fine-tunes metabolism: red–blue mixes enhance pigments and antioxidant potential; modest green fractions improve canopy light distribution and can lower nitrates in leafy greens; far-red modulates morphology and carbohydrate partitioning – beneficial in some fruit vegetables, but excessive doses may disrupt flowering/fruit set. UV-A/UV-B pulses upregulate defense pathways and phenolic synthesis without yield penalties when dosed carefully. Photoperiod scheduling is another practical tool for balancing energy use and quality. Continuous or pulsed strategies can maintain photosynthetic efficiency at lower energy cost and align spectral recipes with developmental stages—blue-enriched for seedlings, small green fractions for leafy biomass and mineral balance, and blue/UV-A support during flowering and ripening to bolster flavor and antioxidant profiles.

Integrating spectral management with plant-specific response curves enables real-time, algorithmic control of metabolic pathways that determine the health potential of vegetables. Emerging systems that unite tunable LEDs with canopy sensors, biochemical feedback, and AI control will enable growers to maximize phytonutrient output per kilowatt-hour while increasing yield, making light management a core practical tool in next-generation greenhouse production.

Greenhouse producers should deploy dynamic, spectrum-optimized lighting—centered on a red–blue foundation with crop-specific additions of green, far-red, and UV-A/UV-B—tuned to DLI targets and growth stages, and coupled with real-time monitoring to optimize nutritional quality, yield, and energy efficiency.

**Keywords:** controlled environment agriculture, greenhouse vegetables, light spectrum, LED technology, photoreceptors, phytonutrients.

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