

LEDs significantly increased flavonoid, phenolic and artemisinin content (Rai et al., 2024) and in lettuce, basil and kale, where red-blue combinations improved antioxidant properties and pigment accumulation (Trivellini et al., 2023).

Far-red light, although less efficient at directly driving photosynthesis, plays a key regulatory role in plant development through phytochrome-mediated signaling pathways, influencing growth, secondary metabolism and phenological responses (Demotes-Mainard et al., 2016). In mint (*Mentha haplocalyx* Briq.), supplementation with far-red light enhanced biomass accumulation and photosynthetic performance while significantly promoting the biosynthesis of phenolic compounds and flavonoids such as luteolin and methylchavicol, suggesting its utility in improving both growth and medicinal value (Yu et al., 2024). Likewise, in basil, night interruption with far-red light increased flavonoid content by over 40% and improved biomass partitioning toward leaves, contributing to enhanced quality and postharvest durability (Fallah et al., 2024). These findings are consistent with meta-analytical evidence showing that moderate far-red supplementation significantly increases plant height, leaf area and dry biomass in vegetable crops, while also modulating nutritional traits like soluble sugars (Zhang et al., 2024).

Although not part of the photosynthetically active radiation (PAR), UV-A radiation plays a pivotal role as an environmental signal, particularly as an elicitor of secondary metabolism. In lettuce, exposure to UV-A-enriched light environments has been shown to significantly enhance the accumulation of phenolic compounds and anthocyanins, along with improved antioxidant capacity, especially when applied during the pre-harvest phase (Tsormpatsidis et al., 2008).

In conclusion, spectral management in hydroponic systems offers a powerful tool to modulate the synthesis of secondary metabolites, enabling the production of high-value crops with enhanced functional properties. Understanding the specific roles of different wavebands is key to designing light recipes that balance productivity with nutritional and sensory quality.

2.5 Light as a tool for abiotic stress management in hydroponic systems

In hydroponic systems, where environmental parameters can be tightly controlled, light becomes not only a driver of photosynthesis but also a powerful modulator of stress responses. Specific light spectra can mitigate the adverse effects of abiotic stresses such as salinity, heat, drought-like conditions and nutrient imbalances (Islam et al., 2021; Soufi et al., 2023), all of which may arise even under soilless cultivation due to recirculating nutrient solutions, equipment malfunction or high evaporative demand.

Blue light has been widely associated with enhanced antioxidant defenses, primarily through the activation of genes encoding antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and peroxidase (POD) (Soufi et al., 2023; Trivellini et al., 2023).

UV-A radiation can act as a priming agent, inducing mild oxidative stress that triggers acclimation responses. In controlled studies with hydroponic kale pre-harvest exposure to combined UV-A radiation and chilling stress enhanced abiotic stress tolerance by increasing phenolic compound accumulation and antioxidant enzyme activity, without compromising growth or photosynthetic capacity (Lee et al., 2019).

Red and far-red light influence phytochrome signaling pathways that regulate stomatal conductance and water-use efficiency (Legris et al., 2019). In aeroponics systems, manipulating the red:far-red ratio has been proposed as a method to reduce transpiration and improve tolerance to short-term water deficit without compromising biomass production (Carotti et al., 2023).

Furthermore, light-nutrient interactions are increasingly recognized as key to optimizing stress resilience. Under nitrogen-limited conditions, combined red and blue light improves nitrogen-use efficiency by enhancing enzymes involved in carbon-nitrogen metabolism. In tomato (*Solanum lycopersicum* L.) seedlings, a 3:1 red:blue ratio upregulated nitrate reductase and glutamine synthetase activity (Wang et al., 2017), while in spinach (*Spinacia*