

2.3 Photobiological responses in hydroponic contexts

In hydroponic systems, the absence of soil and the use of controlled environments allow the isolation and manipulation of light as a single variable, making it an ideal platform to investigate photobiological responses. Under these conditions, plants often display heightened sensitivity to spectral changes due to the stability of other growth factors (Dou et al., 2017).

These responses are mediated by specialized photoreceptors, including phytochromes, cryptochromes, phototropins and UVR8, which together orchestrate a wide range of physiological processes such as seedling de-etiolation, stomatal regulation, and flowering (Folta and Carvalho, 2015).

Recent research in indoor hydroponic systems has examined how varying light intensities, particularly under controlled red and blue LED spectra, influence plant growth and quality. In a study involving basil (*Ocimum basilicum* L.) and lettuce (*Lactuca sativa* L.), increasing the photosynthetic photon flux density (PPFD) from 100 to 300 $\mu\text{mol}/\text{m}^2/\text{s}$ LED to a progressive rise in biomass accumulation, with optimal yield observed at 250 $\mu\text{mol}/\text{m}^2/\text{s}$. Beyond this level, no additional yield gains were reported. Importantly, at 250 $\mu\text{mol}/\text{m}^2/\text{s}$, lettuce exhibited significantly higher antioxidant activity, as well as increased levels of total phenolics and flavonoids. These findings suggest that moderate enhancements in light intensity not only maximize biomass production but also improve the nutritional quality of leafy vegetables grown in controlled indoor environments (Pennisi et al., 2020).

Moreover, manipulating the red:far-red ratio in vertical farming setups can regulate shade-avoidance responses, affecting plant height, leaf expansion and resource partitioning, which has direct implications for optimizing space and uniformity in multilayer production systems (Park and Runkle, 2017).

In summary, a deeper understanding of photoreceptor-mediated signaling and its modulation by artificial spectra is essential for tailoring light recipes that enhance growth, nutritional quality, and stress resilience in soilless crops. Hydroponic cultivation thus provides a unique opportunity to refine photobiological strategies for sustainable and efficient crop production.

2.4 Light quality and secondary metabolism in hydroponic crops

Light quality, particularly spectral composition, plays a critical role in modulating secondary metabolism in plants (Hasan et al., 2017), a set of biochemical pathways that generate compounds such as phenolics, flavonoids, alkaloids and terpenes, many of which are associated with stress tolerance, antioxidant activity and nutritional value (Böttger et al., 2018). In hydroponic systems, the high degree of environmental control offers an ideal context to fine-tune spectral inputs and thereby modulate these metabolic pathways with precision.

Blue light has been shown to influence the biosynthesis of phenolic compounds and flavonoids through the activation of key transcription factors in the phenylpropanoid pathway. This regulation is particularly relevant in leafy greens and culinary herbs, where antioxidant capacity is a core attribute of functional quality. For instance, in hydroponically cultivated japanese mint (*Mentha canadensis* L.), blue light significantly increased the production of monoterpenes such as menthol and menthone, indicating an upregulation of specialized metabolite pathways (Ueda et al., 2021). Similarly, kale (*Brassica oleracea* L. var. *acephala*) microgreens exposed to blue LEDs showed higher levels of phenolic compounds like quercetin and sinapic acid, accompanied by enhanced antioxidant activity (Lee et al., 2023). In basil, studies on microgreens and in vitro cultures confirmed that blue light elevates levels of rosmarinic acid and total phenolics, thus enhancing its nutritional profile (Nazir et al., 2020).

Red light, while primarily promoting photosynthesis and biomass accumulation, generally has a limited effect on secondary metabolism compared to blue or UV-A radiation (Hasan et al., 2017). However, combining red with blue light often produces synergistic effects, enhancing both vegetative growth and bioactive compound production. This has been demonstrated in crops such as sweet wormwood (*Artemisia annua* L.), where red-blue