

particularly relevant in hydroponic systems, where environmental parameters can be fine-tuned to optimize both plant health and functional quality. This study aims to provide an integrative overview of how artificial light quality affects plant photomorphogenesis, secondary metabolism and abiotic stress responses in hydroponic systems. We also discuss emerging technologies that enable dynamic and spectrum-adaptive lighting strategies and explore their potential in precision agriculture applications.

2 Fundamentals of Photobiology in Plants

Light is a fundamental environmental signal that regulates not only photosynthesis but also a wide array of developmental and metabolic processes in plants. Through the perception of specific wavelengths, plants adjust their growth patterns, morphology, resource allocation and stress responses in a process known as photomorphogenesis (Wang et al., 2022). Understanding the photobiological basis of these responses is essential for optimizing artificial lighting strategies in hydroponic systems.

2.1 Photoreceptors and their spectral sensitivity

Plants possess specialized photoreceptors that absorb specific portions of the light spectrum and initiate signaling cascades:

Phytochromes are chromoproteins that perceive red (R: 620-700 nm) and far-red (FR: 700-750 nm) light (Wang et al., 2022). They control seed germination, stem elongation, shade avoidance and flowering. Phytochrome-mediated responses depend on the red:far-red light ratio, a critical indicator of canopy density and competition (Legris et al., 2019).

Cryptochromes and phototropins absorb blue (B: 400-500 nm) and UV-A (320-400 nm) radiation. Cryptochromes are involved in photoperiodic flowering, hypocotyl inhibition, and circadian clock regulation, while phototropins (control phototropism, chloroplast relocation and stomatal opening (Li and Yang, 2007).

UVR8 is a unique UV-B photoreceptor that perceives short-wavelength radiation (280-315 nm) and triggers protective responses including the induction of flavonoid biosynthesis, ROS scavenging enzymes and DNA repair mechanisms (Yin and Ulm, 2017).

These photoreceptors not only regulate specific processes individually but also work in concert to coordinate growth, resource allocation and adaptation to environmental stimuli. Their activity underlies many of the photobiological responses observed in hydroponic crops, as will be discussed in subsequent sections.

2.2 Photosynthesis and the action spectrum

Photosynthetically active radiation (PAR: 400-700 nm) encompasses the range of wavelengths used by photosystems I and II to drive electron transport and CO₂ fixation. Among these, red and blue wavelengths are the most effective for stimulating photosynthesis due to their strong absorption by chlorophyll a and b (Wimalasekera, 2019).

However, green light (500-570 nm), traditionally considered less important due to lower chlorophyll absorption, has gained renewed attention. While not as efficient on a per photon basis, green wavelengths can penetrate deeper into leaf tissues and inner canopy layers, thus supporting photosynthetic activity in shaded leaves, especially in dense or multilayered hydroponic systems. This spatial complementarity enhances whole-plant photosynthetic performance when green light is used in combination with red and blue (Smith et al., 2017).

Understanding the action spectrum, the relative quantum efficiency of different wavelengths for photosynthesis, enables precise tailoring of light spectra in artificial lighting systems. In hydroponic setups, this is particularly valuable to maximize light-use efficiency (LUE), optimize biomass accumulation and reduce energy costs, especially when combined with spectral tuning technologies.