

oleracea L.), blue-green-red light combinations boosted biomass and key nitrogen-assimilating enzymes under low nitrogen supply (Ramezani et al., 2023). In summary, beyond growth promotion, targeted light treatments serve as a non-chemical strategy to improve abiotic stress tolerance in hydroponic crops, contributing to the sustainability and resilience of soilless food production systems.

2.6 Design of lighting strategies in hydroponic systems

Designing effective lighting strategies in hydroponic systems requires an integrative approach that considers spectral quality, light intensity, photoperiod and spatial distribution (Figure 1). Unlike field or greenhouse cultivation, hydroponic systems, especially in fully controlled environments, allow for precise modulation of light parameters, offering a unique opportunity to optimize photosynthetic efficiency and plant quality.

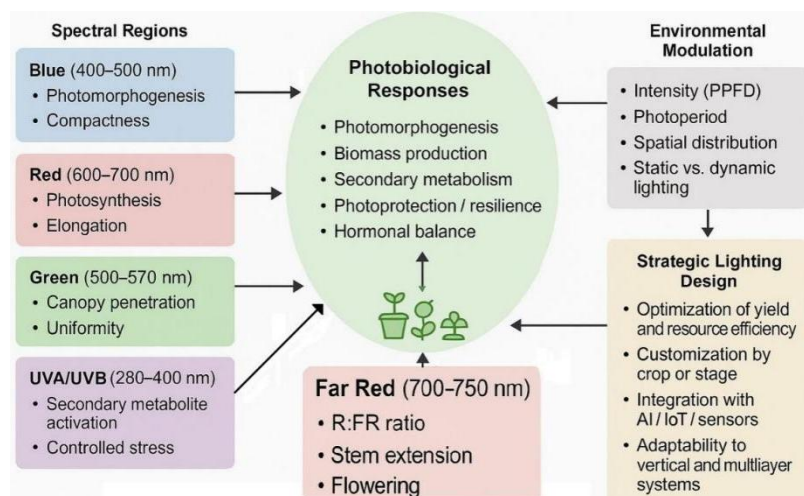


Figure 1 Conceptual diagram summarizing plant photobiological responses to different spectral regions in hydroponic systems and their integration into lighting design strategies for optimizing growth, efficiency and stress resilience

2.6.1 Photoperiod and light intensity

Photoperiod plays a key role in plant development by interacting with circadian rhythms and flowering regulation. Most leafy vegetables and herbs respond positively to long-day photoperiods (e.g., 16 h light / 8 h dark), which promote vegetative growth and delay flowering (Adams and Langton, 2005). This response has been demonstrated in several species, including lettuce, basil and arugula (*Eruca sativa* L.), where a 16-hour photoperiod significantly enhanced foliar biomass and overall yield compared to shorter photoperiods.

Optimal light intensity must be defined according to crop-specific requirements and phenological stage, while ensuring energy efficiency. In general, moderate to high PPFD values (e.g., 200-300 $\mu\text{mol}/\text{m}^2/\text{s}$) are often used in indoor cultivation (Pennisi et al., 2020; Gavhane et al., 2023), although the ideal range may vary. Importantly, increasing light intensity beyond a certain threshold does not always improve yield and may reduce resource-use efficiency (Engler and Krarti, 2021).

2.6.2 Directional lighting

The orientation and positioning of lighting, such as top-down, side-lighting or intercanopy lighting, can significantly impact light interception and canopy uniformity (Stamford et al., 2023). Side-lighting, for example, has been shown to enhance leaf expansion and uniformity in multilayer systems, particularly when green light is included to penetrate deeper into the canopy (Schipper et al., 2023).

2.6.3 Spectral customization

Tailoring the light spectrum according to crop species or development stage is becoming increasingly viable with programmable LED systems. For example, seedling stages may benefit from blue enriched light to promote compact growth (Treder et al., 2016), while reproductive stages may require red and far-red components to