

stimulate flowering (Bojka, 2020). The ability to shift spectral profiles over time allows for fine-tuned control of morphogenesis, metabolism and yield.

In summary, lighting strategy design in hydroponics should go beyond simple illumination and incorporate principles of photobiology, precision agriculture and crop-specific requirements. Thoughtfully designed lighting schemes can enhance both productivity and sustainability in soilless cultivation systems.

3 Agronomic Applications and Case Studies

The application of photobiological principles in hydroponic systems has led to significant advancements in crop performance, particularly for leafy vegetables and herbs. Controlled lighting environments offer the opportunity to optimize plant morphology, nutrient composition and productivity through spectral tuning and light management strategies.

3.1 Light source technologies and their agronomic implications

In hydroponic systems, artificial light sources determine both the quantity and quality of photosynthetically active radiation (PAR), influencing plant morphology, metabolism, and resource-use efficiency. Among the commonly used technologies-light-emitting diodes (LEDs), high-pressure sodium (HPS) lamps, and fluorescent lamps-each differs in spectral characteristics, energy performance, and suitability for various growth stages (Table 1).

Table 1 Comparative overview of artificial light sources used in hydroponic crop production

Technology	Advantages	Limitations
LED	Efficient, tunable spectrum, low heat, long life	High upfront cost
HPS	High light intensity, low initial cost	Inefficient spectrum, high heat; shorter lifespan
Fluorescent	Inexpensive, low heat, effective for propagation	Limited spectrum, lumen decay, not ideal for full cycle

LEDs have become the preferred option for hydroponic cultivation owing to their precise spectral tunability, high photon efficacy and long operational lifespan (50,000-100,000 h). Their ability to finely adjust red and blue light ratios optimizes photosynthesis and enhances the biosynthesis of bioactive compounds, such as phenolics and flavonoids, thereby improving both yield and nutritional quality. In addition, the reduced infrared emissions of LEDs lower canopy temperatures and water demand compared with high-pressure sodium (HPS) systems, contributing to higher overall resource-use efficiency (Dannehl et al., 2021; Knyazeva et al., 2024).

By contrast, HPS lamps emit primarily within the yellow-green spectral region, which is suboptimal for photosynthetic performance. Their high thermal output increases transpiration and water stress in plants, while their relatively short lifespan (10,000-20,000 h) and declining efficiency over time limit their long-term viability for intensive hydroponic production (Dannehl et al., 2021).

Fluorescent lamps, although affordable and characterized by low heat emission, provide limited spectral flexibility and insufficient intensity for full-cycle crop cultivation. Consequently, their use is generally restricted to propagation and early growth stages rather than large-scale or commercial applications (Seiler et al., 2017; Stamford et al., 2023).

In a word, LEDs are emerging as the standard in hydroponic lighting due to resource efficiency and crop-quality enhancements. HPS and fluorescents retain niche uses in propagation or legacy systems but are increasingly being phased out.

3.2 Crop specific responses

Multiple hydroponic studies demonstrate that lighting quality and strategy significantly influence both plant productivity and nutritional composition. In lettuce, comparative experiments under LED versus HPS lighting revealed 15% reduced water consumption under LEDs without compromising yield. Notably, LED treatments increased key phenolic compounds and overall phenolic content compared to HPS (Dannehl et al., 2021). Further, dynamic red and blue LED regimens in lettuce boosted xanthophyll accumulation and enhanced photosynthetic indices and transpiration efficiency (Samuolienė et al., 2021).