***Review Article***

**Influence of Artificial Lighting on Plant Growth in Hydroponic Environments**

**Abstract**

Hydroponics, a soil-less technique of growing plants using nutrient-rich water, is revolutionizing modern agricultural ways for maximizing production per unit area. However, one of the vital challenges that lies inside hydroponic farming is the effective use of synthetic developed lighting fixtures, as the farming is majorly done indoors and in polyhouses environments. The present review explores the significance of lighting on crop dynamics and modern lighting technologies present with the growers. LEDs, fluorescent lamps, high-pressure sodium (HPS) lighting and rising technologies like plasma and induction lighting impart significant effects on plant growth, yield and nutrient uptake. The review also examines the key elements which include light spectrum, depth, and photoperiod, which have a direct impact on photosynthesis and photo-morphogenesis. The paper also highlights the significance of balancing red, blue and inexperienced wavelengths to optimize the plant morphology, biomass accumulation and even biochemical composition. Information on how various lighting conditions alter plant development and physiological responses, and therefore, growers can tune their systems accordingly for fetching maximum yield under hydroponic cultivation. This study emphasizes on importance of smart lighting techniques for enhancing not only crop production but also energy conservation and environmental sustainability.

**Keywords**: Grow light, light spectrum, nutrient uptake, LED, hydroponics

**Introduction**

Hydroponics is a soilless cultivation technique that allows plants to grow in nutrient-rich water solution offering a controlled environment for root development and nutrient absorption. The hydroponic system removes the need for soil and allows plants to grow in nutrient-rich media, nutrients absorbed by suspended roots in nutrient media. Compared to the traditional method, hydroponics provides sustainability through water efficiency, eliminating disease, pest management and land optimization. Checking for water efficiency, traditional farming uses nearly 217 litres of water to grow 1 kg of tomatoes wherein, whereas hydroponic use 70 litres of water and aeroponic even less at just 20 litres water (Zhang, Maruhnich and Folta*,*2011). It is a space utilization system, for growing high-density plantations and vertical farming. Crops are grown in a controlled environment, by providing optimum temperature, nutrients, humidity, and light. By providing a controlled environment, a hydroponic system gives year-round crop production. This will be a promising innovation in modern agriculture. Light is an important factor for plant growth, serving as an energy source for photosynthesis. Other than photosynthesis, photo-morphogenesis also depends on light spectrum, intensity and duration. The intensity and duration of light control the reproductive and vegetative growth of plants. Light is composed of 7 different wavelengths of light (700nm-400nm) in which, red and blue light are essential for photo-morphogenesis and photosynthesis (Paradiso & Proietti, 2021). As this method is *in-vitro* performed, artificial lights are required to fulfil the photosynthesis requirement and plant development. Light-emitting diodes (LEDs) are introduced as they have good energy efficiency, the ability to emit specific light spectra and long lifespan as per plant needs and increase growth rate, biomass production and overall yield of the crop. So, by analyzing the existing research and literature, this review aims to comprehensively examine the role of light in hydroponics systems. The discussion encloses various artificial light sources used in hydroponics, including LEDs, florescent and high-pressure sodium (HPS) lamps and analyzing their effect on plant growth and system efficiency. By synthesizing findings from multiple studies, this paper seeks to provide a comprehensive understanding of how light influences hydroponic cultivation and to identify best practices for maximizing crop yield and quality.

**Light Sources in Hydroponics**

In hydroponic structures selecting the proper light supply is essential for optimizing plant growth and improvement. Diverse lighting technology which includes light emitting diodes (LEDs), fluorescent lights, excessive-pressure Sodium (HPS) lamps, metal Halide (MH) lamps, incandescent bulbs and other alternatives offer awesome blessings and some limitations.

1. **LED lighting**: LEDs have won prominence in hydroponics due to their power performance customizable spectra and extended lifespan. They convert energy into light with minimum heat production decreasing cooling necessities and operational charges. The potential to tailor light wavelengths to precise plant boom stages complements photosynthesis and biomass accumulation. With life spans exceeding 50,000 hours, LEDs limit renovation and replacement costs contributing to sustainable hydroponic farming practices.
2. **Fluorescent lights**: Fluorescent lamps which include T5 and Compact Fluorescent Lamps (CFLs) provide a balance between energy performance and light spectrum exceptional. Emitting an extensive spectrum that closely mimics natural sunlight they may be mainly effective for the duration of the vegetative level due to their high blue light output promoting robust leaf development and stem electricity. Their price-effectiveness makes them appealing to hobbyist and industrial grower, offering sizeable lengthy-term financial savings.
3. **High-pressure sodium (HPS) Lamps**: HPS lamps are conventional lighting sources acknowledged for his or her high lumen output and performance. They emit light mostly within the red and yellow wavelengths, making them perfect for the flowering and fruiting stages of plant boom. However, HPS lamps generate giant warmness, necessitating the right ventilation and cooling systems to maintain the most advantageous growing situations. In spite of better preliminary expenses, their lengthy lifespan and dependable performance have sustained their use in hydroponic structures (Tyler, 2023).
4. **Metal Halide (MH) Lamps**: MH lamps are a subset of high-intensity Discharge (hid) lights emitting light in the blue spectrum that is beneficial throughout the vegetative growth phase. They promote compact furry growth and are frequently used together with HPS lamps to provide a complete spectrum of light in the course of the plant’s life cycle. They are much like HPS lamps as MH lamps produce massive heat and require appropriate cooling measures.
5. **Incandescent Bulbs**: Incandescent bulbs are much less usually used in hydroponic systems due to their inefficiency and high heat output. They emit light across a broad spectrum however lack the intensity and specific wavelengths wished for the greatest plant boom. Their short lifespan and high strength intake cause them to be a less viable alternative as compared to trendy lighting fixtures technology.
6. **Alternative light sources**: rising technology which includes plasma and induction lighting is gaining attention in hydroponics. Plasma lighting simulates natural daylight, supplying a full spectrum that promotes strong growth through high photon flux density and decreases heat emission. Induction lighting, similar to fluorescent lamps but without electrodes, offers long life spans and solid light output. However, those technologies regularly contain higher initial investments and are still under evaluation for huge adoption in hydroponic programs (Tyler, 2023) (Table 1).

**Table 1. Comparative Analysis of Grow Light Types for Hydroponics**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Light type** | **Spectrum coverage** | **Energy efficiency** | **Heat output** | **Common use** | **Advantages** | **Limitation** |
| **LED** | Full spectrum (customizable), often optimized for photosynthesis | Very high; low energy use per light output | Very low | Widely used in all stages of hydroponic growth | Long lifespan, customizable spectrum, low heat, compact | Higher upfront costs and quality varies by brand |
| **Fluorescent Light** | Mostly blue and white light; limited red | Moderate | Low to moderate | Seedlings, leafy greens, indoor hobby systems | It is inexpensive, easy to install, and good for vegetative stage | Lower intensity, not ideal for fruiting/blooming |
| **High-pressure sodium (HPS) Lamps** | Strong in red-orange; poor in blue | Moderate to high | High | Flowering and fruiting phase | Promotes flowering, high light intensity | High heat, less blue light, short lifespan |
| **Metal Halide (MH) Lamps** | Rich in blue and white light; low red | Moderate | High | Early vegetative stage | Encourages leafy growth, better than HPS for seedlings | High heat, requires ballast, which is not energy efficient |
| **Incandescent Bulbs** | Limited; mostly red and yellow | Very low | Very high | Rarely used; only in DIY or temporary setups | Cheap and easy to find | Extremely inefficient, excessive heat, short life |
| **Plasma light** | Broad full spectrum, close to sunlight | High | Moderate | Research labs, high-tech setups | Excellent colour rendering, good spectrum for full growth | Expensive, limited availability, bulky setup |

*(Source: Tyler, 2023)*

the choice of lighting in hydroponic systems depends on factors such as power efficiency, spectrum suitability, warmness output, initial funding, and specific plant requirements. LEDs currently lead in popularity due to their customizable spectra and operational performance while conventional options like HPS and MH lamps remain in use for their tested overall performance. Emerging technologies hold to adapt presenting ability alternatives as their feasibility and price effectiveness are similarly assessed.

**Role of light in photosynthesis and photo-morphogenesis**

Light performs a pivotal position in plant boom and development inside hydroponic structures commonly via its influence on photosynthesis and photo-morphogenesis. Photosynthesis is the manner by way of which plant life converts light power into chemical strength producing carbohydrates essential for increase. Photo-morphogenesis refers to the light-mediated improvement of plant shape and structure. In hydroponic cultivation, in which soil is absent, optimizing light situations will become crucial to ensure strong photosynthetic pastime and suitable morphological improvement (Yang and He,2024). The fineness of light, encompassing its spectral composition considerably affects each photosynthesis and photo-morphogenesis. Specific wavelengths of light serve as alerts that modify plant improvement, shaping and metabolism (Yang and He,2022). As an example, purple and blue wavelengths are acknowledged to steer various factors of plant boom and development. Light depth is another crucial aspect influencing photosynthesis and photo-morphogenesis in hydroponic structures. Ultimate degrees of light depth decorate plant growth and positively affect the regulation of photosynthesis, nutrient absorption, and common plant first-class (Rai, Smriti and Kaushal, 2024). The improvement of the photosynthetic apparatus is also pushed by way of light first-class. Vegetation has developed state-of-the-art sensory systems for light perception, permitting them to regulate boom and development in accordance with the local light environment. Light greatly serves as a motive force for the improvement of the photosynthetic apparatus influencing the performance of photosynthesis.

**Intensity, spectrum and photoperiod**

In hydroponic structures the management of light depth, spectrum and photoperiod play an essential function in enhancing plant growth, improvement, and productivity. Light depth immediately impacts the charge of photosynthesis where flowers utilize light energy to convert carbon dioxide and water into glucose and oxygen. Studies have shown that optimum light depth promotes biomass accumulation, even as immoderate depth can reason photo inhibition, reducing the efficiency of the photosynthetic procedure (Choorappulakkal and Jaglan,2024). For example, research conducted with the aid of Kang, Kumar, Atulba, Jeong and Hwang, (2013) proven that light intensities up to 260 μmol/m²/s notably stepped forward the boom of hydroponically cultivated lettuce. Past this threshold, no notable growth in plant boom was discovered, thus, highlighting the need to balance the energy input with plant requirements to avoid wastage and plant pressure.

The spectral composition of light is similarly crucial in hydroponic cultivation as special wavelengths alter various physiological techniques in plant life. Red light, normally within the range of 600-700 nm, is thought to sell stem elongation, flowering and fruiting, even as blue light (400-500 nm) stimulates chlorophyll synthesis, enhances leaf enlargement, and encourages compact boom. The combination of purple and blue light is widely used in hydroponics to acquire the most reliable boom consequences. Studies highlight that precise light spectra not only have an impact on plant morphology but also have an effect on nutrient composition, antioxidant pastime and secondary metabolite manufacturing (Ritambara *et al.,*2024). As a result, excellent-tuning the light spectrum is critical to attaining crop yields in hydroponic structures.

Photoperiod, the length of light exposure within a 24-hour cycle, similarly affects plant growth, flowering and ordinary productiveness. Vegetation is categorized as quick-day, long-day, or day-impartial species, each responding uniquely to varying light intervals. Hydroponic growers often manipulate the photoperiods to govern flowering levels and vegetative increase. Kang et al. (2013) examined the distinct photoperiods such as 18/6 h (light/dark) nine/3 h and 6/2 h cycles. Their outcomes indicated that longer photoperiods particularly 18/6 h extensively progressed the biomass accumulation in lettuce thus demonstrating the importance of extended light publicity for greater crop performance. The combination of light depth, spectrum and photoperiod in hydroponic structures requires careful calibration to maximize yield great and power performance. Research has indicated that adjusting those parameters together improves plant health and productivity. For instance, research by means of Yang et al. (2024) explored the idea of the everyday light crucial (DLI) which mixes light intensity and photoperiod to obtain the best light exposure. Via enforcing a DLI of 14. four mol/m²/d at some stage in early increase levels and 17.3 mol/m²/d at some stage in rapid boom levels, researchers carried out advanced shoot biomass and typical yield in hydroponic lettuce. Such findings emphasize the significance of synchronizing light parameters to fulfil the specific requirements of vegetation at unique boom degrees. As hydroponic technology boosts, the usage of power-efficient lighting fixture systems like LED furniture, blended with unique management over light intensity, spectrum and photoperiod, maintains to decorate sustainable agricultural practices in managed environments.

**Effects of Different Light Spectra on Plant Growth**

Radiation is the supply of electricity for photosynthesis and affords records for photograph morphogenesis (Shivani et al.,2024). Photosynthesis is pushed by way of photosynthetically energetic radiation (400 to 700 nm). Pigments used by flora to seize photosynthetically energetic radiation for photosynthesis include chlorophyll a, chlorophyll b and an expansion of accessory pigments (Nishio, 2000). The motion spectra of chlorophyll a and b strongly take in red light (RL) and blue light (BL), but, weakly absorb green light (GL) (Nishio, 2000).

**Greenlight**

Green light is a huge portion of solar irradiation and rising data mean that inexperienced wavebands modulate light-caused plant responses. Research from the past 50 years has tested that green light influences plant biomass (Klein, 1965; Morgan and Smith, 1976) and reverses UV Band blue-light-mediated stomatal starting (Frechilla et al.,2000; Eisinger et al.,2003). Unfiltered sunlight hours supply wavelengths starting from UV-A to a protracted pink, wavelengths representing human seen moderate and its flanking energies invisible to the human eye. The wavebands longer than the ones sensed with the resource of human beings (Red, 700-780 nm) are meaningful to the plant. Flowers exhibit high morphological plasticity in reaction to colouration to escape from negative slight environments, which include dense cover or shaded through manner of pinnacle leaves (Franklin, 2008). Early studies of the abundant red wavelength of canopy colour have been shown to affect plant structure via controlling stem elongation, leaf enlargement, leaf hyponasty (important to an extra vertical orientation), petiole elongation and apical dominance (Ballare, 1999)(Morgan and Smith, 1976). The addition of green light to the history of pink and blue moderate added an increase within the petiole period at the rate of the typical leaf period (the leaf blade became smaller) alongside conspicuous leaf hyponasty (Zhang et al.,2011). The commentary that green light delivered on petiole elongation, but, decreased leaf growth is exactly the alternative to the picture’s characteristic (Takemiya et al.,2005). The physiological and genetic proof advices that an opportunity method of sensing inexperienced light can be liable for this reaction. Plant life has grown in enriched inexperienced conditions or under low red a long way red environments display off colour characters but with one in all a type forms of gene expression.

**Seed dormancy and germination**

exclusive plant species show off a selection of responses to blue and green lights on dormancy launch (Goggin and Steadman, 2012). Seeds stratified in some distance-red light have a germination charge close to darkish-stratified seeds. However, seeds stratified in blue moderate hold dormancy irrespective of the presence or absence of a Red. Seemingly green light acts in addition to blue light to inhibit dormancy release in the absence of blue light (Goggin et al.,2008). For the cause that inhibition of dormancy launches between wavelengths of 510 and 550 nm is vulnerable or absent, they proposed that the green light impact at 550 nm changed into in all likelihood mediated through a unique photoreceptor, now not cryptochrome (Goggin and Steadman, 2012). Seeds matured in a shaded environment (low red/a ways-pink) have a decreased germination charge than that matured in an excessive pink to a few a ways-red environment (Dechaine et al.,2009). The observation that inexperienced light inhibits dormancy release is steady with this interpretation.

**Seedling establishment**

Computer-aided photo capture and evaluation has discovered the precise timing of early changes in elongation fee (Parks et al.,2001). The identical imaging system captured an unusual fashion in response to dim inexperienced light, whilst illuminated the seedling growth fee might no longer decrease. Alternatively, the boom of the seedlings modified quicker than the dark fee(Folta, 2004). The equal look moreover showed that seedlings grown underneath dim (<4 µ/m2/s) Red and blue light with inexperienced light had been taller than the ones grown under pink and blue on my own.

**Vegetative growth**

NASA scientists have finished experiments on plant boom to lay suitable lighting fixture systems for the area. One end result recognized that when photosynthetic photon flux was modified into stored consistent, lettuce grown in an aggregate of purple, blue, and green LED slightly had massive leaf location and higher sparkling and dry shoot mass than those grown completely underneath red or blue on my own (Kim, Goins, Wheeler and sager, 2004). Their interpretation of this result is that even though red and blue light are extra powerful for selling photosynthesis, inexperienced light might penetrate plant leaves more effectively and increase carbon fixation (Nishio, 2000; Kim, Goins, Wheeler and Sager, 2004). Terashima, Fujita, Inoue, Chow and Oguchi, (2009) discovered that at high PPF, GL drives leaf photosynthesis greater efficiently than RL and BL.

**Blue light**

have a look conducted through Bian et al.,(2018) indicated that 50 µmol/m2/s or 15 % BL (whichever is more relying on the PPF) is probable required to sell normal improvement in maximum species. Research discovers approximate absolute BL necessities that vary amongst 10 to 15 % BL from the entire PPF produced with the aid of way of the light resources examined. In a take a look at, Nishio, 2000 indicated that growth (dry mass) and leaf vicinity elevated even as BL modified into introduced to a pure RL supply, and accelerated up to 15% BL for lettuce, radish, and pepper. Terashima, Fujita, Inoue, Chow and Oguchi, (2009) observed that decreased dry mass manufacturing underneath natural RL for spinach, radish, and lettuce and that the equal time as dry mass have become improved with the addition of 10 % BL delivered through fluorescent lamps(table 2).

**Table 2. Effect of Red, Blue, and Green Light on Different Crops**

|  |  |  |
| --- | --- | --- |
| **Crop** | **Light spectrum** | **Observed effects** |
| **Lettuce** | Red | Increased leaf area and shoot biomass (Naznin *et al.,* 2019). |
|  | Blue | Enhanced chlorophyll content and antioxidant capacity; reduced leaf expansion (Naznin *et al.,* 2019). |
|  | Green | Supplementation improved photosynthetic capacity and chlorophyll content under continuous light conditions (Bian *et al.,* 2018). |
| **Spinach** | Red | Promoted growth and biomass accumulation (Naznin *et al.,* 2019). |
|  | Blue | Increased pigment content and antioxidant capacity (Naznin *et al.,* 2019). |
|  | Green | The addition of green light to red and blue LEDs decreased growth parameters compared to the red and blue light combination (Nguyen *et al.,* 2021). |
| **Kale** | Red | Increased plant height(Naznin *et al.,*2019). |
|  | Blue | Reduced plant height; enhanced pigment content and antioxidant capacity (Naznin *et al.,* 2019). |
| **Basil** | Red | Promoted growth and biomass accumulation (Naznin *et al.,* 2019). |
|  | Blue | Increased chlorophyll content and antioxidant capacity (Naznin *et al.,* 2019). |
| **Cucumber** | Red | Increased plant height and leaf area; enhanced photosynthetic efficiency (Nguyen *et al.,* 2021). |
|  | Blue | Improved seedling quality and nutrient content; reduced stem elongation (Nguyen *et al.,* 2021). |
| **Tomato** | Red | Increased fruit biomass and radiation-use efficiency (Ke *et al.,* 2024). |
|  | Blue | Enhanced photosynthetic rate and fruit biomass when combined with red light (Ke *et al.,*2024). |

**Challenges and Limitations of Lighting in Hydroponic Systems**

Hydroponic systems, which domesticate flora without soil by providing nutrient-rich water answers, have won prominence in current agriculture because of their efficiency and area-saving blessings. However, the reliance on artificial lighting fixtures in those structures introduces demanding situations related to strength consumption, heat management and the optimization of light parameters to make sure the highest quality plant increases and yields.

1. **High Energy Demand and Cost of Artificial Lighting**

Artificial lights are critical in hydroponic structures, especially in indoor vertical farms wherein herbal daylight is restricted or absent. The strength consumption related to those light structures is great, often constituting a large part of operational prices. For instance, in vertical farming setups, lights can account for approximately 50% to 65% of the overall power utilization. This excessive power demand not handiest escalates operational costs but also increases issues approximately the environmental effect, specifically when the strength is sourced from non-renewable power. The sort of lighting fixture generation hired notably affects power consumption and charges. Traditional light structures which include excessive-strain sodium (HPS) lamps, have been broadly used however are frequently less power-efficient compared to trendy alternatives like light-emitting diodes (LEDs). A look at evaluating those lighting fixtures systems observed that, depending on the capture situation, the most green HPS furnishings had a lower common annual 5-12 months cost in line with photon than the maximum green LED furnishings. Despite the better preliminary investment, LEDs offer blessings including a longer lifespan and the potential to tailor light spectra to specific plant needs, doubtlessly main to strength savings and advanced crop yields through the years. However, the efficiency of LEDs is not always absolute; modern-day designs convert about 55% of electrical strength into light, with the closing 45% dissipated as warmness, necessitating extra strength for cooling in indoor environments.

1. **Heat Stress and Its Impact on Plant Growth**

The heat generated by using artificial light systems can cause multiplied temperatures inside hydroponic environments, and thus, doubtlessly causing warmth pressure in plant life. Heat stress adversely influences plant physiological methods, consisting of photosynthesis, respiratory, and transpiration, leading to reduced increase charges, lower yields and compromised crop niches. In indoor vertical farms where an area is restricted the accumulation of heat from lighting fixtures structures can hastily elevate ambient temperatures growing challenging situations for maintaining the most efficient plant increase environments. Coping with warm pressure entails enforcing effective climate control techniques, along with ventilation, air conditioning and the usage of heat sinks. Additionally, selecting light systems with higher strength-to-light conversion efficiencies can reduce excess warmth production. For instance, while LEDs are greater efficient than traditional lighting fixture systems, they still convert a portion of electricity into warmness, necessitating consideration of heat dissipation mechanisms within the design of hydroponic systems.

1. **Balancing Light Intensity, Spectrum, and Photoperiod for Optimal Yield**

Accomplishing surest plant growth in hydroponic systems calls for cautious calibration of light depth, spectrum, and photoperiod. Light intensity, measured as photosynthetic photon flux density (PPFD), at once affects photosynthesis prices. Studies have shown a near correlation between the fresh weight of lettuce and PPFD degrees ranging from 100 to 250 μmol/m2/s when illuminated with warm white light and 660 nm pink LEDs for a sixteen-hour photoperiod. The light spectrum additionally performs a critical position in plant development. Blue and pink wavelengths are often absorbed via chlorophyll and power photosynthesis, even as green light penetrates deeper into the cover, improving photosynthesis in lower leaves. In dense canopies typical of hydroponic systems, incorporating inexperienced light can improve typical light distribution and utilization. Moreover, the spectral high-quality of light influences other plant responses, inclusive of stem elongation, leaf expansion, and flowering time, necessitating a balanced spectrum tailor-made to particular crop requirements. Photoperiod is the period of light publicity which regulates plant circadian rhythms and impacts methods like flowering and vegetative growth. For example, lettuce grown beneath a 16-hour photoperiod with appropriate light spectra has established the finest increase and yield. Adjusting photoperiods to align with the photoperiodic responses of unique vegetation can enhance productiveness and resource use performance.

**Discussion**

The usage of artificial lighting in hydroponic structures has converted current agriculture by enabling controlled surroundings crop production. Our review clearly indicates that the light spectrum plays a critical role in influencing not only plant growth but additionally, physiological processes which include nutrient uptake, pigment synthesis, and yield. Red and blue light, being the most studied wavelengths, continuously display a strong impact on photosynthesis and plant morphology. Red light tends to inspire stem elongation and flowering, even as blue light complements leaf improvement, chlorophyll production, and antioxidant pastime. Green light, even though less absorbed, has also proven subtle consequences, mainly in aggregate with other spectra, indicating that it could play a supportive role in deep canopy penetration and biomass accumulation. Distinct forms of growth lights- consisting of LEDs, fluorescent lamps, HPS, MH lamps, incandescent bulbs, and plasma lights offer particular benefits and limitations. LEDs emerge as the maximum promising because of their customizable spectrum, low warmness output, and excessive energy efficiency. In comparison, conventional lights like HPS and MH are more power-intensive and generate more warmness, making them less perfect for small or enclosed hydroponic setups. But, they still discover use in huge-scale greenhouses wherein heat may be managed or even applied in cold climates.

Integrating light spectrum control with hydroponic nutrient delivery allows growers to the best conditions for optimum efficiency. Light impacts root interest and may affect the uptake of key minerals like nitrogen, magnesium, and iron. This opens exciting avenues for "light recipes" that can be customized to beautify both yield and nutritional first-rate. Ordinary, the proof strongly supports that strategic manipulation of the light spectrum, intensity, and length in hydroponic systems can appreciably enhance crop performance. As technology evolves, smarter lighting systems will possibly become necessary for sustainable and precision agriculture, particularly in regions going through land and water constraints.

**Conclusion**

In hydroponic systems, synthetic lighting plays a pivotal role in replacing daylight to guide plant boom, improvement and productiveness. This evaluation highlights how unique forms of light sources in particular LED have transformed hydroponic cultivation by allowing precise manipulation over light depth, spectrum, and photoperiod. Know how every light wavelength influences photosynthesis and plant behaviour at varying rates enables the growers to tune their lighting setups for maximum efficiency and yield. While traditional lighting fixtures like HPS and MH lamps are still used because of their established performance, contemporary technology like LEDs offer greater electricity performance, decreased warmness output, and customizability making them ideal for sustainable indoor farming. The significance of light management is further emphasized using its impact on plant morphology, nutrient uptake, and biomass accumulation. As the hydroponic era advances, destiny achievement will depend on continued innovation in grow lights, integrating medical studies with practical applications to provide greater meals using fewer resources.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

**References**

Ballaré, C. L. (1999). Keeping up with the neighbours: phytochrome sensing and other signalling mechanisms. *Trends in plant science*, *4*(3), 97-102.

Bian, Z., Yang, Q., Li, T., Cheng, R., Barnett, Y., & Lu, C. (2018). Study of the beneficial effects of green light on lettuce grown under short‐term continuous red and blue light‐emitting diodes. *Physiologia plantarum*, *164*(2), 226-240.

Choorappulakkal, J., & Jaglan, P. Optimizing Hydroponics Farming: A Comprehensive Review of AI and IoT Integration for Enhanced Efficiency and Sustainability.

Dechaine, J. M., Gardner, G., & Weinig, C. (2009). Phytochromes differentially regulate seed germination responses to light quality and temperature cues during seed maturation. *Plant, cell & environment*, *32*(10), 1297-1309.

Eisinger, W. R., Bogomolni, R. A., & Taiz, L. (2003). Interactions between a blue‐green reversible photoreceptor and a separate UV‐B receptor in stomatal guard cells. *American Journal of Botany*, *90*(11), 1560-1566.

Franklin, K. A. (2008). Shade avoidance. *New Phytologist*, *179*(4), 930-944.

Frechilla, S., Talbott, L. D., Bogomolni, R. A., & Zeiger, E. (2000). Reversal of blue light-stimulated stomatal opening by green light. *Plant and Cell Physiology*, *41*(2), 171-176.

Goggin, D. E., & Steadman, K. J. (2012). Blue and green are frequently seen: responses of seeds to short-and mid-wavelength light. *Seed Science Research*, *22*(1), 27-35.

Goggin, D. E., Steadman, K. J., & Powles, S. B. (2008). Green and blue light photoreceptors are involved in maintenance of dormancy in imbibed annual ryegrass (Lolium rigidum) seeds. *New Phytologist*, *180*(1), 81-89.

Kang, J. H., KrishnaKumar, S., Atulba, S. L. S., Jeong, B. R., & Hwang, S. J. (2013). Light intensity and photoperiod influence the growth and development of hydroponically grown leaf lettuce in a closed-type plant factory system. *Horticulture, Environment, and Biotechnology*, *54*, 501-509.

Kaushal, S. (2024). Cultivating Resilience: Exploring Root Systems in Hydroponic Agriculture. *J. Exp. Agric. Int*, *46*(5), 915-925.

Ke, X., Yoshida, H., Hikosaka, S., & Goto, E. (2024). Effect of red and blue light versus white light on fruit biomass radiation-use efficiency in dwarf tomatoes. *Frontiers in Plant Science*, *15*, 1393918.

Kim, H. H., Goins, G. D., Wheeler, R. M., & Sager, J. C. (2004). Green-light supplementation for enhanced lettuce growth under red-and blue-light-emitting diodes. *HortScience*, *39*(7), 1617-1622.

Klein, R. M., Edsall, P. C., & Gentile, A. C. (1965). Effects of near ultraviolet and green radiations on plant growth. *Plant Physiology*, *40*(5), 903.

Morgan, D. C., & Smith, H. (1976). Linear relationship between phytochrome photoequilibrium and growth in plants under simulated natural radiation. *Nature*, *262*(5565), 210-212.

Naznin, M. T., Lefsrud, M., Gravel, V., & Azad, M. O. K. (2019). Blue light added with red LEDs enhance growth characteristics, pigments content, and antioxidant capacity in lettuce, spinach, kale, basil, and sweet pepper in a controlled environment. *Plants*, *8*(4), 93.

Nguyen, T. P. D., Jang, D. C., Tran, T. T. H., Nguyen, Q. T., Kim, I. S., Hoang, T. L. H., & Vu, N. T. (2021). Influence of green light added with red and blue LEDs on the growth, leaf microstructure and quality of spinach (*Spinacia oleracea* L.). *Agronomy*, *11*(9), 1724.

Nishio, J. N. (2000). Why are higher plants green? Evolution of the higher plant photosynthetic pigment complement. *Plant, Cell & Environment*, *23*(6), 539-548.

Paradiso, R., & Proietti, S. (2022). Light-quality manipulation to control plant growth and photomorphogenesis in greenhouse horticulture: The state of the art and the opportunities of modern LED systems. *Journal of Plant Growth Regulation*, *41*(2), 742-780.4

Rai, A., Smriti, S., & Kaushal, S. (2024). Utilising crop residues as hydroponic media for sustainable food production system. *International Journal of Research in Agronomy*, *7*(4), 73-78.

Ritambara, Shubham and Kaushal, S. 2024. Expanding horizons: Exploring the potential of Dutch bucket hydroponics. *International Journal of Research in Agronomy* 7(11), 204-207.

Takemiya, A., Inoue, S. I., Doi, M., Kinoshita, T., & Shimazaki, K. I. (2005). Phototropins promote plant growth in response to blue light in low light environments. *The Plant Cell*, *17*(4), 1120-1127.

Terashima, I., Fujita, T., Inoue, T., Chow, W. S., & Oguchi, R. (2009). Green light drives leaf photosynthesis more efficiently than red light in strong white light: revisiting the enigmatic question of why leaves are green. *Plant and cell physiology*, *50*(4), 684-697.

Tyler A. 2023. Hydroponics Lighting: Unleash the Power of Optimal Plant Growth.

Yang R, Yang H, Ji F and He D. 2024. Enhancing the Photon Yield of Hydroponic Lettuce Through Stage-Wise Optimization of the Daily Light Integral in an LED Plant Factory. *Agronomy* 14(12), 2949.

Yang, J., Song, J., & Jeong, B. R. (2022). Lighting from top and side enhances photosynthesis and plant performance by improving light usage efficiency. *International Journal of Molecular Sciences*, *23*(5), 2448.

Zhang T, Maruhnich SA and Folta KM. 2011. Green light induces shade avoidance symptoms. *Plant physiology* 157(3), 1528-1536.