***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 way for maximizing production per unit area. However, one of the vital challenges lies inside hydroponic farming is the effective use of synthetic developed lighting fixtures, as the farming is majorly done indoors and in poly houses environments. Present review explores the significance of lighting on crop dynamics and modern lighting technologies present with the growers. LED’s, fluorescent lamps, high-pressure sodium (HPS) lighting and rising technologies like plasma and induction lighting impart significant effect on plant growth, yield and nutrient uptake. Review also examines the key elements which include mild spectrum, depth and photoperiod, which have 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 alters 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 the crop production but also for energy conservation and environmental sustainability.

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

**Introduction**

Hydroponics is a soilless cultivation technique that allows the plants to grow in nutrients rich water solution offering a controlled environment for root development and nutrient absorption. Hydroponic system removes the need of soil and allowing plants to grow in nutrient rich media, nutrient absorbed by suspended roots in nutrient media. Comparing to traditional method, hydroponics provides sustainability by water efficiency, eliminating disease, pest management and land optimization. Checking for water efficiency, traditional farming uses nearly 217 liters of water to grow 1 kg of tomatoes wherein, hydroponic uses 70 liters of water and aeroponic even less at just 20 liters water (Zhang *et al.,*2011). It is space utilization system, by growing high-density plantation and vertical farming. Crops are grown in controlled environment, by providing optimum temperature, nutrient, humidity, and light. By providing controlled environment, hydroponic system gives year-round crop production. This will be promising innovation in modern agriculture. Light is an important factor for plant growth, serving as energy source for photosynthesis. Other than photosynthesis, photo-morphogenesis also depends on light spectrum, intensity and duration. These intensity and duration of light controls reproductive and vegetative growth of plant. Light is composed of 7 different wavelength 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 fulfill the photosynthesis requirement and plant development. Light-emitting diodes (LED’s) are introduced as they have good energy efficiency, ability to emit specific light spectra and long lifespan as per plant needs and increases growth rate, biomass production and overall yield of crop. So, by analyzing the existing research and literature, this review aims to comprehensively examine the role of light in hydroponics system. 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 finding from multiple studies, this paper seeks to provide a comprehensive understanding of how light influence hydroponic cultivation and to identify best practices for maximizing crop yield and quality.

**Light Sources in Hydroponics**

In hydroponic structures selecting the proper mild supply is essential for optimizing plant growth and improvement. Diverse lighting technology which includes mild light emitting diodes (LED’s), 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**: LED’s 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 mild 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 includes T5 and Compact Fluorescent Lamps (CFL’s) provide a balance among the 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 for each hobbyist and industrial growers, 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 mild mostly within the crimson and yellow wavelengths, making them perfect for the flowering and fruiting stages of plant boom. However, HPS lamps generate giant warmness, necessitating right ventilation and cooling systems to maintain 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 mild 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 mild in the course of the plant’s lifestyles 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 greatest plant boom. Their short lifespan and high strength intake cause them to a less viable alternative as compared to trendy lighting fixtures technology.
6. **Alternative light sources**: rising technology which includes plasma and induction lighting are gaining attention in hydroponics. Plasma lighting simulates natural daylight, supplying a full spectrum that promotes strong growth thru high photon flux density and decrease heat emission. Induction lighting, similar to fluorescent lamps however 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. 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 cost, quality varies by brand |
| **Fluorescent Light** | Mostly blue and white light; limited red | Moderate | Low to moderate | Seedlings, leafy greens, indoor hobby systems | Inexpensive, easy to install, 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, 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 color 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. LED’s currently lead in popularity due to their customizable spectra and operational performance while conventional options like HPS and MH lamps remain in use for his or her tested overall performance (table 1). 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 structure commonly via its influence on photosynthesis and photo-morphogenesis. Photosynthesis is the manner by way of which plant life convert mild power into chemical strength producing carbohydrates essential for increase. Photo-morphogenesis refers to the mild-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 *et al.,* 2024; Shubham *et al.,* 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 *et al.,* 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 the plant growth and positively affect the regulation of photosynthesis, nutrient absorption, and common plant first-class (Kochetova *et al.,* 2022; Rai *et al.,* 2024). The improvement of the photosynthetic apparatus is also pushed by way of mild 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 mild 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 plays an essential function in enhancing plant growth, improvement, and productivity. Mild 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 *et al.,*2024). for example, research conducted with the aid of Kang *et al.,*(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 became discovered, and thus, highlighting the need to balance the energy input with plant requirements to avoid wastage and plant pressure.

The spectral composition of mild is similarly crucial in hydroponic cultivation as special wavelengths alter various physiological techniques in plant life. Crimson 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 mild is widely used in hydroponics to acquire most reliable boom consequences. Studies highlights that precise light spectra not best have an impact on plant morphology however additionally have an effect on nutrient composition, antioxidant pastime and secondary metabolite manufacturing (Ritambara *et al.,*2024). As a result, excellent-tuning the mild spectrum is critical to attaining the 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 mild 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 (mild/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 and 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 have 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 mild crucial (DLI) which mixes light intensity and photoperiod to obtain best mild 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 mild parameters to fulfill the specific requirements of vegetation at unique boom degrees. As hydroponic technology boost, the usage of power-efficient lighting fixtures systems like LED furniture, blended with unique manage 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 seven-hundred 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 crimson mild (RL) and blue mild (BL), but, weakly absorb green mild (GL) (Nishio, 2000).

**Green light**

inexperienced light is a huge portion of the solar irradiation and rising data mean that inexperienced wavebands modulate light caused plant responses. research of past 50 years have tested that green light influences plant biomass (Klein, 1965; Morgan and Smith, 1976) and reverses UV Band blue-mild-mediated stomatal starting (Frechilla et al.,2000; Eisinger et al.,2003). Unfiltered sunlight hours supplies 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 (crimson, ~seven hundred-780 nm) are meaningful to the plant. flowers shows excessive morphological plasticity in reaction to coloration to escape from negative slight environments, which include dense cover or shaded through manner of pinnacle leaves (Franklin, 2008). Early studies at the abundant a red wavelengths of canopy color have been shown to affect plant structure via controlling stem elongation (Morgan and Smith, 1976 ), leaf enlargement, leaf hyponasty (important to an extra vertical orientation), petiole elongation and apical dominance (Ballare, 1999 ). Addition of green light to the history of pink and blue moderate added on a increase within the petiole period at the rate of typical leaf period (the leaf blade became smaller) alongside conspicuous leaf hyponasty (Zhang et al.,2011). The commentary that green mild delivered on petiole elongation, but, decreased leaf growth is exactly the alternative of picture’s characteristic (Takemiya et al.,2005). The physiological and genetic proof advice that an opportunity method of sensing inexperienced light can be liable for this reaction. plant life grown in enriched inexperienced conditions or under low red a long way red environments display off color 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 mild on dormancy launch (Goggin and Steadman, 2012). Seeds stratified in some distance-crimson mild 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 crimson mild. seemingly green mild acts in addition to blue light to inhibit dormancy release in the absence of blue mild (Goggin et al.,2008). For the cause that inhibition of dormancy launch 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 thru a unique photoreceptor, now not cryptochrome (Goggin and Steadman, 2012). Seed matured in a shaded environment (low red/a ways-pink) has a decrease germination charge than that matured in a excessive pink to a few a ways-red environment (Dechaine et al.,2009). The observation that inexperienced mild 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 mild, whilst illuminated the seedling growth fee might no longer decrease. alternatively, boom of the seedlings modified into quicker than the dark fee(Folta, 2004). The equal have a look at moreover showed that seedlings grown underneath dim (<4 µ/m2/s) crimson and blue mild with brought 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 layout suitable lighting fixtures systems for area. One end result recognized that when photosynthetic photon flux modified into stored consistent, lettuce grown in an aggregate of purple, blue, and green LED slight had massive leaf location and higher sparkling and dry shoot mass than those grown completely underneath red or blue on my own (Kim et al.,2004). Their interpretation of this give up result is that even though crimson and blue light are extra powerful for selling photosynthesis, inexperienced mild might penetrate plant leaves more effectively and increase carbon fixation (Nishio, 2000; Kim et al.,2004). Terashima et al. (2009) who discovered that at high PPF, GL drives leaf photosynthesis greater efficiently than RL and BL.

**Blue light**

have a look at 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 variety amongst 10 to 15 % BL from the entire PPF produced with the aid of way of the mild resource’s 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 et al. (2009) observed that decreased dry mass manufacturing underneath natural RL for spinach, radish, and lettuce and that on the equal time as dry mass have become improved with the addition on 10 % BL delivered through fluorescent lamps.

**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 | Addition of green light to red and blue LEDs decreased growth parameters compared to 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 through providing nutrient-rich water answers, have won prominence in current agriculture because of their efficiency and area-saving blessings. But, the reliance on artificial lighting fixtures in those structures introduces demanding situations related to strength consumption, heat management and the optimization of mild parameters to make sure highest quality plant increase and yield.

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 lights 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 fixtures generation hired notably affects power consumption and charges. Traditional lights 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 (LED’s). A have a look at evaluating those lighting fixtures systems observed that, depending at 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, LED’s offer blessings including longer lifespan and the potential to tailor mild spectra to specific plant needs, doubtlessly main to strength savings and advanced crop yields through the years. However, the efficiency of LED’s is not always absolute; modern-day designs convert about 55% of electrical strength into mild, 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 lights 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 nice. In indoor vertical farms where area is restricted the accumulation of heat from lighting fixtures structures can hastily elevate ambient temperatures growing challenging situations for maintaining most efficient plant increase environments. Coping with warmth pressure entails enforcing effective climate control techniques, along with ventilation, air conditioning and the usage of heat sinks. Additionally, selecting lights systems with higher strength to light conversion efficiencies can reduce excess warmth production. As an instance, while LED’s are greater efficient than traditional lighting fixtures 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. Mild intensity, measured as photosynthetic photon flux density (PPFD), at once affects photosynthesis prices. studies have shown a near correlation among 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 mild spectrum additionally performs a critical position in plant development. Blue and pink wavelengths are often absorbed via chlorophyll and power photosynthesis, even as green mild penetrates deeper into the cover, improving photosynthesis in lower leaves. In dense canopies typical of hydroponic systems, incorporating inexperienced mild can improve typical light distribution and utilization. moreover, the spectral high-quality of mild 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 mild 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 finest increase and yield. Adjusting photoperiods to align with the photoperiodic responses of unique vegetation can enhance productiveness and resource use performance.

**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 mild sources in particular LED’s have transformed hydroponic cultivation through allowing precise manipulate over mild depth, spectrum, and photoperiod. Know how every light wavelength influences the photosynthesis and plant behavior at varying rates and enables the growers to tune their lighting setups for maximum efficiency and yield. while traditional lighting fixtures structures like HPS and MH lamps are nevertheless used because of their established performance, contemporary technology like LED’s offer greater electricity performance, decrease warmness output, and customizability making them ideal for sustainable indoor farming. The significance of mild management is further emphasized by means of its impact on plant morphology, nutrient uptake and biomass accumulation. As hydroponic era advances, destiny achievement will depend on continued innovation in grow lights, integrating medical studies with practical applications to provide the greater meals using fewer resources.

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