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Article

Evaluation of LED Systems for controlled spectral lighting in indoor hydroponic cultivation

Evaluación de Sistemas LED para iluminación espectral controlada en cultivos hidropónicos de interior

Juárez-Balderas, Mario Alberto [a], Daniel-Eufracio, América Abigail [b], Araiz-Aguilar, Gustavo Rafael [c] and Villaseñor-Aguilar, Marcos Jesús [d]

[a] ROR Tecnológico Nacional de México/Campus Irapuato • S-8744-2018 • 0000-0002-5756-5403 • 99207
[b] ROR Tecnológico Nacional de México/Campus Irapuato • 0009-0003-3141-6017
[c] ROR Tecnológico Nacional de México/Campus Irapuato
[d] ROR Tecnológico Nacional de México/Campus Irapuato • 0009-0003-0598-8145 • 294911 |

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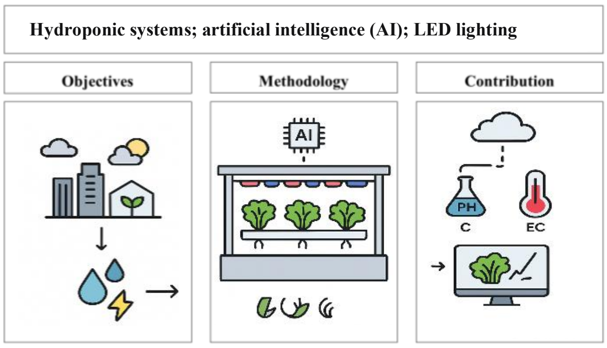
* ✉ [mario.jb@irapuato.tecnm.mx]

Abstract

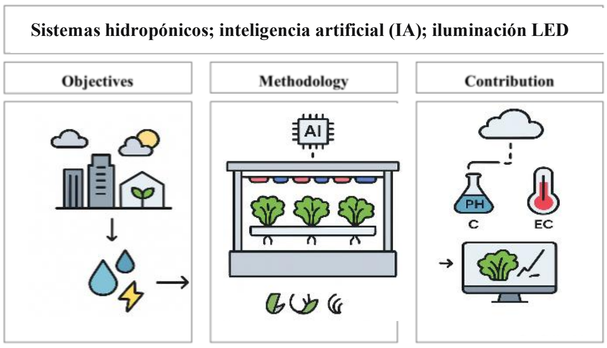
Indoor farming is emerging as a practical solution to challenges such as urbanization, limited arable land, and climate change, enabling sustainable, efficient, and localized food production. LED lighting has taken on a key role in hydroponic systems by allowing precise spectral control that enhances photosynthesis, morphological development, and the nutritional quality of crops. This article examines how LED spectral design influences the growth of lettuce [Lactuca sativa], emphasizing its benefits in terms of energy efficiency and resource optimization. Additionally, the integration of emerging technologies like artificial intelligence [AI] and the Internet of Things [IoT] is explored. These technologies enable real-time adjustment of critical variables such as light intensity, pH, electrical conductivity, and temperature through predictive algorithms including deep neural networks, fuzzy logic, and LSTM models. Such tools not only boost operational efficiency but also help reduce water, fertilizer, and electricity consumption. Furthermore, the use of computer vision systems has proven effective in monitoring the physiological state of plants and detecting potential deficiencies or anomalies without the need for manual intervention.



Hydroponic systems; artificial intelligence [AI]; LED lighting

Resumen

La agricultura interior se posiciona como una solución viable frente a desafíos como la urbanización, la escasez de suelo cultivable y el cambio climático, al permitir una producción sostenible, eficiente y localizada, la iluminación LED ha adquirido un papel estratégico en sistemas hidropónicos, al posibilitar un control espectral preciso que mejora la fotosíntesis, el desarrollo morfológico y la calidad nutricional de los cultivos. Este artículo analiza la influencia del diseño espectral LED sobre el crecimiento de lechuga [Lactuca sativa], destacando sus ventajas en términos de eficiencia energética y optimización de recursos .Asimismo, se explora la integración de tecnologías emergentes como la inteligencia artificial [IA] y el Internet de las Cosas [IoT], que permiten ajustar en tiempo real variables críticas como la intensidad de luz, el pH, la conductividad eléctrica y la temperatura, mediante algoritmos predictivos como redes neuronales profundas, lógica difusa y modelos LSTM. Estas herramientas no solo aumentan la eficiencia operativa, sino que también reducen el consumo de agua, fertilizantes y electricidad. Además, el uso de sistemas de visión computacional ha demostrado ser eficaz para monitorear el estado fisiológico de las plantas y anticipar posibles deficiencias o anomalías sin intervención manual.



Sistemas hidropónicos; inteligencia artificial [IA]; iluminación LED

Area: Development of strategic leading-edge technologies and open innovation for social transformation

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Introduction

Indoor agriculture has emerged as a key strategy in response to global challenges such as urbanization, limited arable land, and climate change. It enables sustainable, continuous food production as the urban population is projected to reach 8.6 billion by 2050, with 80% living in cities. This approach offers viable solutions for local food production, reducing transport-related emissions, and optimizing space use [Aydin et al., 2023]. The loss of soil fertility due to urban expansion and the indiscriminate use of agrochemicals has driven the adoption of soilless systems like hydroponics.

This method allows vertical farming using nutrient solutions and can save up to 90% of water compared to traditional methods [Regmi et al., 2024]. These systems are not only climate-resilient, operating in controlled environments that lessen the impact of irregular rainfall or extreme temperatures, but also reduce the use of pesticides and fertilizers due to a closed and monitored setting. This improves crop health and lowers pollutant emissions [Bamidele et al., 2024]. Energy efficiency has improved with the use of low-consumption LED lighting and smart control systems powered by artificial intelligence [AI], which allow dynamic adjustment of light intensity and the integration of alternatives like solar energy [Kuankid et al., 2022].

Technologies like the Internet of Things [IoT] and AI have transformed these systems by automating the monitoring and control of key variables such as pH, temperature, humidity, CO_2, and electrical conductivity. Connected sensors and actuators enable precision agriculture, increasing yield, reducing resource waste, and improving traceability [Gutiérrez et al.,2021]. AI is also used to diagnose plant diseases, predict harvests, and optimize operations in automated greenhouses. Indoor agriculture offers an integrated solution to the pressures of a changing world, establishing itself as a resilient, efficient, and future-ready production model.

One of the plants commonly used in indoor hydroponic systems is lettuce [*Lactuca sativa*]. Its compact morphology, fast growth, and high photosynthetic efficiency under controlled conditions make it an ideal crop for testing artificial lighting technologies, nutrient solutions, and soilless production systems.

Lettuce has been widely used as a model crop in artificial lighting research. Studies have shown that variations in the LED spectrum particularly the ratio of red, blue, and far-red light significantly affect leaf elongation, nitrate accumulation, and chlorophyll content, making it a reference plant for studying the relationship between light and nutritional quality.

Multiple studies have documented how specific combinations of red, blue, and far-red light influence leaf development, biomass accumulation, and photosynthesis. Factors such as light intensity [PPFD], photoperiod, and even pulsed lighting directly impact lettuce yield, helping reduce energy consumption without compromising quality. The controlled environment also enables the management of nitrate accumulation and the application of machine learning models, such as CNNs [*Convolutional Neural Networks*] for visual analysis and DNNs [*Deep Neural Networks*] for general predictive modeling from diverse data.

These tools are used to estimate growth, detect diseases, or dynamically adjust lighting and nutrients based on the crop's physiological state. Lettuce serves as an ideal bioindicator for validating smart agriculture technologies in controlled environments. [Budavári et al., 2024].

From an agronomic perspective, lettuce has a short cycle [30–45 days from transplant], tolerates high planting densities, and has low nutrient demands [optimal EC of 0.8–1.2 mS/cm], which is the safe nutrient range in water for proper growth. It is sensitive to light spectrum and duration, making it suitable for studying specific responses to light control. Lettuce prefers moderate temperatures [18–22 °C], a pH range of 5.5–6.5, and a photoperiod of 12–16 hours, which can be efficiently supplied with multispectral LED lighting.

These traits have supported its integration into NFT systems [nutrient film technique], floating rafts, and urban vertical modules, giving it an advantage over other crops.

Photobiological requirements of plants

Light is essential for plant growth and quality. It acts as an energy source for photosynthesis and as a signal that triggers photomorphogenesis and other physiological, biochemical, and molecular responses [Bantis et al., 2023; Bayat et al., 2018].

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Indoor horticulture uses LEDs to control spectrum, intensity, and duration, optimizing crop performance and plant photobiology. [Bantis et al., 2023; Paradiso et al., 2022; Marondedze et al., 2018], The key photobiological requirements of plants that can be controlled through lighting are:

Absorption Spectra

Chlorophyll A and B: Chlorophyll molecules are the primary photosynthetic pigments that absorb light photons. Leaves containing chlorophyll show peak absorption around 432 nm [blue] and 670 nm [red] [Tavares et al., 2017]. This absorption is critical for photosynthesis. Light in the red and blue regions of the spectrum is mainly absorbed by photosynthetic pigments, accounting for about 90% of the total leaf absorption [Thi et al., 2019].

Phytochromes: These photoreceptors are sensitive to red and far-red light. Far-red light [730 nm], although outside the photosynthetically active range [400–700 nm] [Motogaito et al., 2017], plays a key role in shifting phytochromes into their red-absorbing form [Mena et al., 2018]. Phytochromes regulate processes such as stem elongation, branching, leaf expansion, and reproduction [Paradiso et al., 2022]. It has also been observed that plants require relatively low phytochrome photoequilibrium values to trigger flowering [Mena et al., 2018].

Cryptochromes and Phototropins: These photoreceptors are activated by blue light [430–450 nm] and mediate responses such as phototropic curvature, inhibition of elongation growth, chloroplast movement, stomatal opening, and seedling development regulation [Bantis et al., 2023; Paradiso et al., 2022]. Blue light also influences chlorophyll biosynthesis and photosynthetic processes [Paradiso et al., 2022].

Carotenoids: These pigments absorb blue light and act as photoprotective agents by rapidly dissipating the excited state of chlorophyll [Thi et al., 2019; Tavares et al., 2017].

Figure 1 shows the relative spectral absorption of plant pigments. The absorption profiles represented are:

- Chlorophyll A [dark green]: peaks at ~430 nm and ~662 nm
- Chlorophyll B [light green]: peaks at ~453 nm and ~642 nm
- β-Carotene [orange]: peak at ~470 nm
- Phytochrome [red]: peaks at ~660 nm and ~730

Box 1

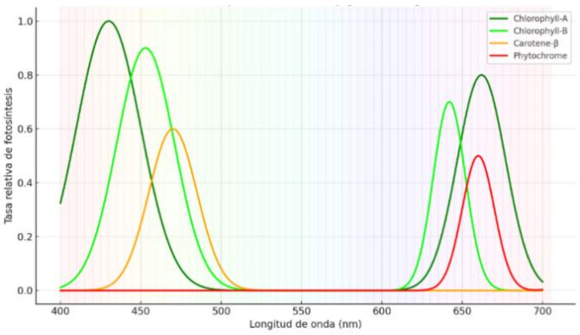

Figure 1

Spectral Absorption in Plant Pigments

Source: Own elaboration

Photomorphogenesis and Phototropism

Photomorphogenesis refers to the complex process by which light, through specific signals, regulates plant development, form, and metabolism [Paradiso et al., 2022]. This includes the adjustment of morphological and physiological traits to adapt to different light conditions. Light quality plays a key role in this process.

For example, low radiation intensity can increase specific leaf area [SLA] and plant height to maximize light absorption for photosynthesis, while high radiation intensity can reduce SLA and increase leaf thickness to protect the plant and maintain efficient photosynthesis [Thi et al., 2019].

Phototropism is the plant's response to light direction, mediated by photoreceptors activated by blue light [Kozai et al., 2018]. This response is essential for directing plant growth toward an optimal light source.

PPFD [Photosynthetic Photon Flux Density] and DLI [Daily Light Integral]

PPFD [Photosynthetic Photon Flux Density] is defined as the number of photons within the 400 to 700 nm wavelength range.

It is a key metric because these photons drive glucose production, which determines the photosynthesis rate [Motogaito et al., 2017]. An average PPFD of 100–300 µmol m^{-2} s^{-1} with a photoperiod of 10–18 hours is suitable for most leafy vegetables grown in plant factories [Kozai et al., 2018]. Studies with spinach have found that a PPFD of 190 µmol m^{-2} s^{-1} may be optimal for growth [Motogaito et al., 2017].

DLI [Daily Light Integral] represents the total amount of photosynthetically active photons a plant receives over the course of a day [Kozai et al., 2018]. Studies have shown that a DLI of 17.3 $mol \cdot m^{-2} \cdot d^{-1}$ under LED lighting with a red/blue ratio [R/B] of 6/5—where red light supports biomass accumulation and blue light promotes healthy morphological development—resulted in higher fresh and dry weight in hydroponically grown spinach, along with improved energy efficiency [Semenova et al., 2023].

An adequate DLI ensures that plants receive the total photon input needed to maintain photosynthesis near its maximum rate for most of the day, without reaching levels that cause photoinhibition. Increasing DLI, combined with proper PPFD and photoperiods, is essential for promoting plant growth [Kelly et al., 2020]. DLI is expressed in $mol \cdot m^{-2} \cdot d^{-1}$ and can be calculated using the following equation.

$$PPFD \times horas\ de\ luz \left(DLI = PPFD\ \frac{fotoperiodo}{10^6} \right) (1)$$

Where t is the exposure time in seconds per day [for example, 14 hours = 50,400 s], the factor 10^6 converts micromoles to moles.

This approach allows light intensity and duration to be adjusted for each phenological stage to maximize photosynthetic efficiency. Studies have shown that, for crops like lettuce, a moderate PPFD [100–250 $\mu mol \cdot m^{-2} \cdot s^{-1}$] and an optimized DLI [14–17 $mol \cdot m^{-2} \cdot d^{-1}$] under extended light periods [16–20 h/day] promote greater biomass, denser leaves, and better photochemical efficiency [ΦPSII], compared to high-PPFD, short-photoperiod scenarios that reduce efficiency [Palmer et al., 2020]. Additionally, photomorphogenesis which includes responses such as elongation, leaf thickness, chlorophyll development, and stretching is mediated by photoreceptors sensitive to red, blue, and far-red light [phytochromes and cryptochromes].

These receptors regulate key hormonal and genetic pathways related to optimal structure, phenology, defense, and thermoregulation [Li et al., 2023].

g/Wh metric: Indicates the energy efficiency of a crop, expressing how many grams of plant biomass are obtained per watt-hour of electrical energy consumed in the system.

The combined use of PPFD and DLI enables the development of customized "light recipes" for different species, growth stages, and production goals, improving system energy efficiency and crop performance.

Comparison of Lighting Technologies

HPS, CFL vs. LED: Spectrum, Energy Use, Heat Dissipation

Light is a key factor in controlled growing systems, influencing physiological, biochemical, and molecular processes through photomorphogenesis. The selection of artificial lighting sources must consider the emitted spectrum, energy efficiency, and heat dissipation [Chutimanukul et al., 2022].

HPS lamps [High Pressure Sodium] mainly emit in the red-orange range [~580–650 nm], supporting flowering but offering limited effectiveness during vegetative stages. CFLs [compact fluorescent lamps] provide a broader spectrum, though with lower intensity and photon efficiency.

LEDs can emit specific wavelengths [red 660 nm, blue 450 nm, green 510 nm] or full-spectrum light [Chutimanukul et al., 2022; Priya et al., 2023].

This spectral flexibility allows light to be tailored to the physiological needs of different species, such as basil or lettuce, where specific red-to-blue light ratios affect biomass accumulation, secondary metabolite production, and photosynthetic parameters [Shareef et al., 2024].

Figure 2 shows a spectral comparison of lighting technologies used in hydroponic cultivation.

Box 2

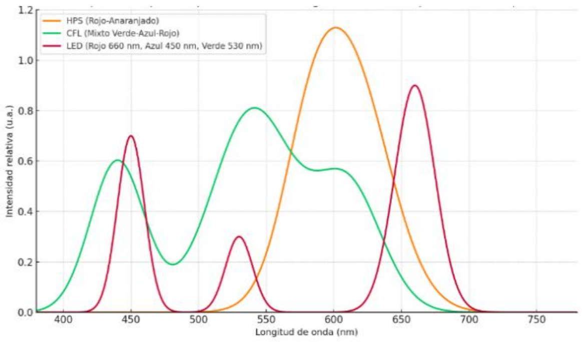

Figure 2

Spectral Comparison of Lighting Technologies in Hydroponic Cultivation

From an energy standpoint, LEDs offer efficiencies above 2.0 µmol/J, compared to 1.0–1.7 µmol/J for HPS and 0.5–1.0 µmol/J for CFLs [Chutimanukul et al., 2022; Shareef et al., 2024; Naim et al., 2020]. This efficiency, combined with lower ventilation needs, significantly reduces total electricity consumption. In LEDs, heat dissipation is concentrated at the heat sink, allowing for localized thermal management, unlike the radiated heat from HPS lamps, which can alter the crop microclimate.

Types of LEDs used in horticulture

Among the available technologies, light-emitting diodes [LEDs] stand out for their ability to emit specific spectra with high energy efficiency and low heat dissipation, which has driven their adoption in precision horticulture [Chutimanukul et al., 2022; Shareef et al., 2024]. LED lighting systems used in hydroponic horticulture are mainly divided into:

Monochromatic LEDs: Emit specific wavelengths [e.g., red 660 nm, blue 450 nm, far-red 730 nm]. Used in controlled spectrum studies.

Extended [Full-Spectrum] LEDs: Mimic sunlight with a balanced mix of red, green, blue, and far-red light. Ideal for full-cycle crops.

Narrow-Band Tuned LEDs: Engineered to target specific photosystems [PSI and PSII] or regulate phytochromes and cryptochromes.

Box 3

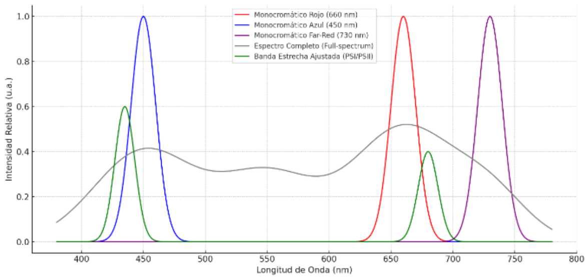

Figure 3

Comparison of LED Spectra in Indoor Horticulture

LED light intensity can be controlled through pulse-width modulation [PWM], enabling dynamic photoperiods and adjustment of daily light integral [DLI]. Automated management using microcontrollers and light sensors helps maintain consistent and reproducible environmental conditions [Putra et al., 2024; Stevens et al., 2023].

With modular design, precise spectral control, and PWM regulation, LEDs are a versatile tool for optimizing crops in smart hydroponic systems [Catota-Ocapana et al., 2024]. These technologies improve not only energy-use efficiency but also the quality of secondary metabolites and morphological uniformity [Mohamed et al., 2021; Pennisi et al., 2019].

Technical advantages of LED

LEDs allow for the adjustment of both light intensity and spectral profile. This feature enables the use of specific wavelengths red [~660 nm], blue [400–500 nm], and green [~510 nm] individually or in combination, as well as full-spectrum lighting. Red light is associated with biomass accumulation and storage compounds [sugars, starches], especially in crops like basil under 3R:1B ratios.

Blue light, on the other hand, regulates stomatal opening and can promote leaf compactness and the synthesis of antioxidants and phenolic compounds, particularly effective at higher blue ratios [1R:3B] [Chutimanukul et al., 2022].

Green light has been linked to increased vitamin C and polyphenol synthesis, and can support biomass production in certain ratios [e.g., 2R:1G:2B] [Shareef et al., 2024].

These spectral configurations can be tailored to the phenological and physiological needs of specific crops like lettuce or basil, maintaining optimal PPFD levels [~200 $\mu mol \cdot m^{-2} \cdot s^{-1}$] and improving the efficiency of light energy use [Yanes et al., 2022].

Types of light treatments

Light treatment design in hydroponic systems considers key variables such as photosynthetic photon flux density [PPFD], energy consumption, and thermal management of LEDs, along with physiological and photosynthetic parameters: net photosynthetic rate [Pn], stomatal conductance [gs], quantum yield of Photosystem II [ΦPSII], and electron transport rate [ETR]. Fresh and dry biomass [FW/DW] provides a direct measure of productivity under different spectral ratios, helping identify optimal configurations specific to each cultivar.

Box 4

Table 1

Effects of Light Spectrum on Lettuce]

LED spectrum	Effect on yield	Effect on nutritional quality	Energy efficiency [g/Wh or µmol/J]
Red [R]	It stimulates stem elongation and leaf expansion; it increases biomass when combined with blue.	It increases sugar accumulation; it reduces nitrate content.	High photosynthetic efficiency when combined with blue; good g/Wh ratio.
Blue [B]	It promotes plant compactness, increases leaf area, and enhances efficient photosynthesis.	It improves phenolic content and antioxidant capacity; activates the phenylpropanoid pathway.	High quantum efficiency in photosynthetic pigments; moderate energy consumption.
Far-red [FR]	It promotes leaf expansion and radiation capture; no direct effect on photosynthesis.	It does not directly improve quality but promotes conditions for nutrient accumulation.	Low quantum efficiency; useful in low doses to complement the spectrum.
UV-A [315-400 nm]	It can induce mild stress, stimulating the production of secondary compounds [phenols, anthocyanins].	It induces the synthesis of flavonoids and polyphenols through stress; high nutraceutical potential.	Very low photosynthetic efficiency; its use should be limited and controlled.

LED spectra influence stem elongation, the accumulation of pigments like chlorophyll and carotenoids, and the synthesis of secondary metabolites, as shown in Table 1. These include phenolic compounds, essential oils such as methyl eugenol and caryophyllene, and antioxidants, whose concentrations can be modulated through spectral adjustments. The relationship between light composition and metabolic profiles opens up opportunities to design lighting schemes aimed at improving crop quality [Taha et al., 2022].

Box 5

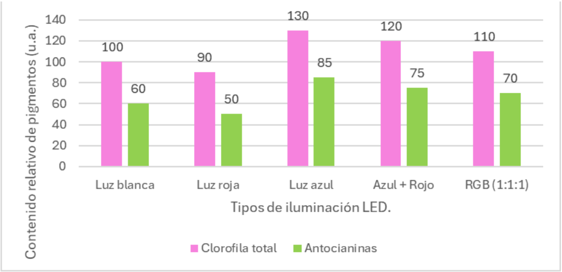

Figure 4

Effect of LED light spectrum type on total chlorophyll and anthocyanin accumulation in lettuce.

In Fig. 5, blue light alone produced the highest total chlorophyll [130 relative units] and anthocyanin levels [85 relative units], significantly exceeding other color combinations, such as white light [100 and 60, respectively] or red light [90 and 50]. Mixed schemes, including blue + red or balanced RGB [1:1:1], showed intermediate results but remained below those obtained under pure blue light [Soufi et al., 2023].

Combinations like 2R:1G:2B have been linked to increases in biomass and photosynthetic pigments [Yanes et al., 2022]. Specific spectral treatments using 1R:1B, 3R:1B, 1R:3B, and 2R:1G:2B have been widely tested. Results indicate cultivar-dependent responses affecting biomass, photosynthesis, secondary metabolite accumulation, and pigmentation. While most studies focus on red, blue, and green wavelengths, other ranges such as far-red and ultraviolet [UV] are also recognized for their potential, mainly in optical sensor-based monitoring [Putra et al., 2024].

The most commonly used spectra in Lactuca sativa include:R:B = 3:1: Promueve biomasa y eficiencia en uso del agua [Pennisi et al., 2019].

R:B = 9:1: Aumenta sacarosa, reduce nitratos [Matysiak et al., 2021].

R:B+FR: Mejora morfología y arquitectura foliar, y puede aumentar área foliar [Legendre & van Iersel, 2021].

In the field of precision horticulture, various LED light treatments have been designed to modulate key physiological processes in crops. Among the most studied spectral combinations are 1R:1B, 3R:1B, 1R:3B, and 2R:1G:2B, which enable targeted control over growth, morphogenesis, secondary metabolite synthesis, and system energy efficiency. The combination of these bands, referred to as a “spectral recipe,” is adjusted based on species, cultivar, and phenological stage.

This approach helps optimize photosynthetic performance, plant architecture, and the nutritional content of the crop [Chutimanukul et al., 2022; Shareef et al., 2024]. Adjusting the light spectrum and photoperiod using LEDs is essential in controlled-environment agriculture, as it allows regulation of physiological processes such as photosynthesis, growth, and flowering. Tailoring light duration and intensity to each growth stage improves both crop performance and overall system efficiency [Reyes et al., 2022].

Photoperiod control

Photoperiod is defined as the daily duration of light exposure. Plants perceive it through photoreceptors such as phytochromes and cryptochromes, which regulate the transition between phenological stages. In controlled environments, the photoperiod can be adjusted artificially.

There are three types of photoperiodic responses:

Short-day plants: flower when the photoperiod is shorter than a specific threshold.

Long-day plants: require a longer light duration to induce flowering.

Day-neutral plants: flowering is independent of photoperiod length.

Adjusting the photoperiod allows synchronization of flowering and maturation [phenological stages] with production goals, reduces light-induced stress, and helps control biomass accumulation and secondary metabolite synthesis. Additionally, photoperiod control can be combined with dimming [intensity regulation] to avoid overexposure by adjusting light intensity.

Integrated control of light spectrum and photoperiod is a strategic tool to maximize the physiological and biochemical performance of plants. It is considered an essential practice in high-efficiency controlled-environment agriculture [Taha et al., 2022; Yanes et al., 2022; Stevens et al., 2023].

Spectral characterization and efficiency in lighting systems for smart hydroponics

In controlled-environment cultivation systems, spectral characterization and photonic efficiency of lighting systems are key variables for optimizing plant growth. The use of LEDs enables precise spectral design and control over light intensity, directly influencing photosynthesis, biomass accumulation, and secondary metabolite synthesis [Chutimanukul et al., 2022; Shareef et al., 2024].

In such systems, photonic efficiency and spectral characterization are critical. LED systems with spectral peaks at 660 nm [red], 450 nm [blue], and 525 nm [green] allow modulation of photosynthesis, morphogenesis, and metabolite biosynthesis.

Their effects have been validated in hydroponic crops such as lettuce, basil, and strawberries. Although the full width at half maximum [FWHM] is not always reported, it is generally estimated to range between 15 and 25 nm in horticultural LEDs.

For environmental monitoring, sensors like the AS7265x offer a spectral resolution of 30 nm, which is useful for assessing lighting conditions, though it does not exactly match the emission profile of the LEDs [Yanes et al., 2022; Taha et al., 2022; Putra et al., 2024].

Photosynthetic photon efficacy [PPE] in commercial LED-based systems—whether white or multi-band-has been reported between 1.8 and 2.7 µmol·J^{-1} [Singh et al., 2015].

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The reviewed studies primarily focus on the use of photosynthetic photon flux density [PPFD] as a practical metric, reporting:

200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for basil and strawberry [Chutimanukul et al., 2022].

150–250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for lettuce [Stevens et al., 2023].

160–190 $\mu mol \cdot m^{-2} \cdot s^{-1}$ óptimal fos Chinese Cabbage [Taha et al., 2022].

In System like NutriSpec, an average PPFD of 330 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with 12 h/day equivalent a DLI of 14 $mol \cdot m^{-2} \cdot day^{-1}$[Yanes et al., 2022].

Although lux sensors are used in some implementations, this unit—based on human visual perception—does not accurately reflect photosynthetic effectiveness. Estimating PPFD from lux requires knowledge of the light source's spectrum and the application of empirical conversion factors, which limits its accuracy in scientific settings [Singh et al., 2015]. While LEDs emit minimal surface heat, thermal management—either passive or active—is necessary to prevent spectral drift. Maintaining an operating temperature around 25 °C is recommended to ensure spectral stability [Putra et al., 2024].

Effects of Different Spectra on *Lactuca sativa*

Spectral lighting influences the growth and quality of *Lactuca sativa* in indoor hydroponics. It analyzes how red, blue, green, and combined spectra modulate morphology, nutritional composition, and energy efficiency.

Morphological performance under different spectra

Morphological performance under different spectraThe morphological growth efficiency of Lactuca sativa in controlled hydroponic systems largely depends on the applied light spectrum, as well as associated intensity and photoperiod. Various studies have identified an optimal photosynthetic photon flux density [PPFD] range of 150 to 250 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for vegetative development in lettuce [Chen et al., 2021; Shareef et al., 2024].

Specifically, a PPFD of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ with a 16-hour photoperiod has been reported to support balanced and sustained growth in leafy crops such as lettuce and basil [Putra et al., 2024].

The application of LED spectra in controlled hydroponic cultivation allows modulation of several physiological processes in Lactuca sativa, including morphogenesis, secondary metabolism, and light energy use efficiency. Spectral adjustment is a key strategy for tailoring lighting to different phenological stages and production goals.

Red light [R], with a peak at 660 nm, promotes the accumulation of carbohydrates such as sucrose and starch, but its exclusive use may induce excessive elongation of hypocotyls and cotyledons, compromising plant structure [Pennisi et al., 2019]. Blue light [B, 400–500 nm] promotes a more compact architecture by influencing stomatal opening, which contributes to transpiration control and leaf thickness [Yanes et al., 2022].

Green light [G, ~510 nm], although traditionally less studied, has shown complementary effects. In combinations such as 2R:1G:2B, improvements have been observed in fresh weight [FW] and shoot elongation, outperforming conventional R:B setups [Chutimanukul et al., 2022; Shareef et al., 2024].

This combination also supports the accumulation of pigments and secondary metabolites such as polyphenols. From an agronomic perspective, smart hydroponic systems show improved biomass and morphological traits compared to traditional systems. Experimental data show differences in plant height [28 cm vs 27.5 cm] and fresh weight [216 g vs 161.2 g] under controlled lighting conditions [Putra et al., 2024].

A PPFD of 330 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 12 h/day, equivalent to a daily light integral [DLI] of 14 $mol \cdot m^{-2} \cdot d^{-1}$, is adequate for maintaining photosynthetic activity in lettuce [Stevens et al., 2023]. Regarding secondary metabolism, blue light has been shown to activate the phenylpropanoid pathway and increase phenolic content in red lettuce. Likewise, the 2R:1G:2B spectrum has been associated with higher levels of polyphenols and vitamin C, suggesting a positive interaction between G and B in the biosynthesis of functional compounds [Shareef et al., 2024].

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Spectroscopic studies have shown that reflectance in visible bands decreases with increasing macronutrient [N, P, K] levels, while near-infrared reflectance [720–1300 nm] increases, indicating greater leaf area and water content [Taha et al., 2022].

In terms of energy efficiency, R:B ratios such as 90:10 have been shown to optimize sucrose accumulation and reduce nitrate content, improving the biomass-to-energy ratio [Pennisi et al., 2019].

Configurations such as R:B=3:1 have been effective for maximizing growth without compromising nutritional quality. Additionally, [Palmer and van Iersel [2020]] found that extending the photoperiod while keeping the DLI constant reduces the required PPFD, increasing system lighting efficiency.

Far-red light [FR] has been proposed as a complementary spectrum to enhance radiation capture and light use efficiency [RUE]. FR has been shown to increase leaf area and photon absorption without significantly increasing energy consumption [Legendre & van Iersel, 2021].

Full-spectrum white light, while less efficient in terms of biomass per watt, offers operational and ergonomic advantages. This limitation can be addressed through intelligent control systems such as diffuse lighting or Random Forest-based models, which have demonstrated 70–90% reductions in water and energy use in NFT/DWC systems [Budavári et al., 2024; Gutierrez Leon et al., 2019].

A comparative summary of studies on LED lighting in hydroponic lettuce [Lactuca sativa] includes details on light spectra, PPFD, photoperiod, LED type, and main physiological responses observed in the plant.

Box 6

Table 2

Comparison between LED configurations and responses in *Lactuca sativa*

LED Spectrum	PPFD [µmol/m^2/s]	Photoperiod [h/day]	Tipo de LED	Physiological Response	APA Reference
R:B:G = 70:18:12	160	16	Multispectral RGB	Higher biomass with 70:18:12; no effect on nitrates.	Matysiak et al. [2021]
R+B [435+663 nm], ±G	60–270	16	Combined Monochromatic	↑ Photosynthesis with B435 + R663; B/R = 1.25:1, ↑ Phenolics	Mohamed et al. [2021]
R:B = 60:40 ± FR	200 + FR 50	18	Mixed + FR	More blue = ↑ nutrients; FR = ↑ biomass, but ↓ phenolics	Van Brenk et al. [2024]
White, R+B, R+B+F R+G, ±UV-B	250	16	Varied Multispectral	White = ↑ yield; R + B = ↑ phenolics; FR = bolting	Alrajhi et al. [2023]
R:B = 3:1	215	16	Combined Monochromatic	R:B = 3:1 optimizes biomass and water use	Pennisi et al. [2019]
R:B = 90:10	200	16	Combined Monochromatic	R:B = 90:10 = ↑ sucrose, ↓ nitrates, good efficiency	Chen et al. [2021]
R+B base ± FR [700–800 nm]	207 + FR	16	Mixed + FR	FR = ↑ leaf area, ↑ biomass per photon	Legendre & van Iersel [2021]
Continuous R + B ± Green	CL [24h]	24 [continuous]	R+B vs. R+B+G	Green reduces CL stress, ↑ photosynthesis	Bian et al. [2018]
R, B, R+B [4:1], FL	~100	16	Monochromatic vs. Combined vs. FL	B and R + B improve seedlings, resulting in more robust plants after transplanting	Johkan et al. [2010]
Pure Red vs. R + B	150 [est.]	14–16	Monochromatic vs. Combined	Adding blue = ↑ chlorophyll, antioxidants, and biomass	Naznin et al. [2019]

Source [Own elaboration]

Emerging technological aspects: IoT, dynamic spectral control, PWM, and DLI automation

Modern hydroponic cultivation systems increasingly rely on the integration of advanced technologies to optimize both plant growth and energy efficiency.

Internet of Things [IoT]: Microcontroller-based platforms such as ESP32, Arduino, and Raspberry Pi are used for remote and automated monitoring of key parameters including pH, electrical conductivity [EC], temperature, and light intensity, with data transmitted to cloud platforms such as Azure IoT Hub and ThingSpeak [Hadj et al., 2023; Fisher et al., 2022].

Some implementations report the use of 6LoWPAN architectures with master-slave control schemes for efficient remote lighting management.

Dynamic spectral control: Although still emerging, this approach appears in studies combining spectral data from nutrient solutions with AI models—such as MH-cDCGAN—to dynamically adjust lighting conditions [intensity, spectrum, and photoperiod] in real time. A spectroscopic IoT system has also been developed to monitor nitrogen content in hydrogels, laying the groundwork for comparable spectral control strategies.

PWM [Pulse-Width Modulation]: This technique is already used to regulate actuators [pumps, motors, mobile sensors] in Arduino-controlled hydroponic systems and is directly applicable to LED intensity control, enabling precise and energy-efficient light modulation.

DLI Automation [Daily Light Integral]: While explicit DLI control is not yet widely adopted, advanced IoT systems integrate light sensors and predictive algorithms to optimize daily light duration and intensity. A recent study on lettuce cultivation reported a 20% improvement in energy efficiency and a 15% yield increase through dynamic light adjustments based on plant growth stage [Nezha Kharraz et al., 2025].

Neural networks for modeling plant growth based on LED spectrum

Convolutional Neural Networks [CNNs] have proven to be highly effective tools for image analysis, particularly in contexts requiring automated extraction of complex visual features. In hydroponic agriculture, their application has gained relevance by enabling accurate assessment of plant growth and physiological status through real-time image capture [Priya et al., 2023].

One of the key capabilities of CNNs is their ability to analyze leaf color, size, shape, and texture with a level of detail that allows these features to be directly correlated with the type and intensity of LED light applied in the cultivation environment. This not only supports continuous visual monitoring of plant development but also provides valuable insights into plant responses to specific spectral variations [Alrajhi et al., 2023; Chen et al., 2021].

Visual detection and assessment of plant status

CNNs process plant images to recognize visual patterns that reflect plant health status. This capability has been successfully applied in the early detection of diseases, water stress, nutrient deficiencies, and chemical imbalances. Recent studies report that these models can achieve over 95% accuracy in identifying pests and diseases, and up to 98.5% accuracy in diagnosing nutrient deficiencies including nitrogen, phosphorus, potassium, iron, calcium, and zinc based on visible symptoms on leaves [Priya et al., 2023].

In hydroponically grown lettuce, for example, RGB image analysis using architectures such as VGG16 and VGG19 has been applied to estimate nutrient concentrations. These models have demonstrated accuracies ranging from 87.5% to 100%, depending on the cultivar and image quality, making them reliable tools for agronomic monitoring [Budavári et al., 2024].

Integration with lighting and sensor data

The true value of CNNs in these systems lies in their ability to correlate plant visual features with lighting conditions. By integrating visual data with sensor inputs collected via IoT platforms such as temperature, humidity, electrical conductivity [EC], pH, and light intensity it is possible to establish direct relationships between plant physiological responses and the applied LED spectral configurations [Chen et al., 2021].

This combined approach helps identify how specific wavelengths or intensity levels affect leaf color, morphology, or texture. Based on these correlations, lighting can be dynamically adjusted to optimize plant development, contributing to improved energy efficiency and more effective crop cycle planning.

Real-time intelligent spectral control using recurrent neural networks

While Convolutional Neural Networks [CNNs] have proven effective for visual analysis of plant development, Recurrent Neural Networks [RNNs] and Long Short-Term Memory [LSTM] models offer a different approach focused on temporal prediction. These algorithms process sequential data from environmental sensors and historical crop records, enabling the anticipation of changes in light demand before they impact plant physiology [Putra et al., 2024; Kharraz et al., 2025].

The key innovation lies in the ability of RNNs/LSTMs to detect evolving patterns not immediately apparent. For example, they can identify microfluctuations in leaf growth rate associated with slight spectral mismatches and project their cumulative effect on biomass and lettuce quality over the following days [Chen et al., 2021; Kelly, Choe, Meng, & Runkle, 2020].

This enables preemptive LED spectrum adjustments to avoid suboptimal lighting periods that could impair photosynthesis or alter morphology.

Another distinctive feature is the capacity to correlate multiple dynamic variables such as air temperature, relative humidity, root zone temperature, and variations in actual photoperiod simultaneously [Gutierrez Leon, et al., 2023].

Using this data, LSTM models generate predictive profiles of physiological response, identifying which combinations of wavelengths and light intensities are likely to be most efficient in the next crop stage [Kuankid & Aurasapon, 2022]. This approach does not rely on fixed rules but evolves progressively with the plant, minimizing both energy consumption and unnecessary exposure to non-beneficial spectra.

RNNs also support zonal lighting strategies within greenhouses by recognizing that different areas may experience microclimatic variations. Rather than applying a uniform light spectrum across the entire crop, the system customizes light intensity and spectral ratio for each zone based on historical data and projected growth [Catota-Ocapana, el at , 2024].

This level of control is still underexplored in the literature and represents a promising direction for energy optimization.

When integrated with embedded controllers, these recurrent networks enable spectral micro-adjustments at minute-level intervals, allowing synchronization of artificial lighting with finer physiological rhythms such as stomatal opening pulses or activation of specific metabolic pathways [Kharraz et al., 2025; Hadj et al., 2023].

This transforms LED lighting into a dynamic, adaptive component capable of modulating not only structural growth but also nutritional quality parameters such as antioxidant or phenolic compound accumulation [Mohamed, Latif, & Ali, 2021]. The use of RNN/LSTM models goes beyond basic automation, constituting a predictive control system where each lighting decision is based on the crop's temporal evolution rather than isolated instantaneous values [Putra et al., 2024; Kharraz et al., 2025].

As such, this approach—still largely unexplored in commercial systems—points toward self-regulating greenhouses that optimize yield, energy efficiency, and product quality simultaneously.

Conclusions

Indoor agriculture is emerging as a resilient and sustainable solution to global challenges such as climate change, urbanization, and the loss of arable land. The integration of hydroponic systems with automated environmental control enables not only the efficient use of water and nutrients but also improves crop quality and traceability while reducing emissions and minimizing agrochemical use.

Technologies such as IoT and machine learning enhance productivity by enabling precision agriculture in urban environments, with lettuce serving as an ideal bioindicator for evaluating plant responses to light spectra, nutrient availability, and controlled conditions. Light management is one of the critical factors for optimizing productivity in controlled environments. Photomorphogenesis and phototropism—regulated by photoreceptors such as phytochromes, cryptochromes, and phototropins—explain how plants perceive and respond to light quality, intensity, and direction.

This knowledge, applied through metrics such as PPFD and DLI, supports the development of tailored light recipes that maximize photosynthetic efficiency and crop quality. For instance, moderate PPFD levels [100–250 µmol×m⁻²×s⁻¹] and optimized DLIs [14–17 mol×m⁻²×d⁻¹] have been shown to promote higher biomass and photochemical yield in lettuce while reducing energy consumption.

The differential spectral response of pigments such as chlorophyll A and B, carotenoids, and phytochromes reinforces the need for adjustable spectra that combine red, blue, and far-red wavelengths to drive leaf elongation, biomass accumulation, or flowering control.

The implementation of predictive models based on recurrent neural networks [RNN/LSTM] introduces an additional layer of optimization by forecasting lighting needs from historical growth, temperature, and DLI data.

This enables real-time synchronization of spectral quality, light intensity, and photoperiod with the plant's circadian and phenological rhythms. Such predictive capabilities not only improve growth and energy efficiency but also support adaptive self-regulation of the system, reducing manual intervention and dynamically adjusting light exposure to optimize photosynthesis and yield.

In terms of lighting technology, LEDs have become the most versatile and efficient alternative compared to HPS and CFL systems. Their ability to emit specific wavelengths [e.g., red 660 nm, blue 450 nm, far-red 730 nm] and full-spectrum light with low heat dissipation makes them ideal for controlled environments. When combined with predictive algorithms and IoT systems, dynamic lighting recipes can be implemented that respond to current conditions and anticipate future metabolic demands, optimizing yield [g/Wh] and crop nutritional quality.

The synergy between plant physiological knowledge [photomorphogenesis, phototropism, and photobiology], lighting metrics [PPFD and DLI], predictive models [RNN/LSTM], and multispectral LED technology establishes a new paradigm in indoor agriculture.

This integrated model transforms lighting into a dynamic, responsive input capable of inducing specific morphophysiological responses, maximizing energy efficiency, and supporting a scalable, adaptive, and sustainable production system.

Lettuce, as a model crop, demonstrates the potential for these strategies to be applied to more complex species, pointing toward the development of intelligent, self-regulating greenhouses that simultaneously optimize growth, quality, and resource use.

References

Basic

Alrajhi, A., Assiri, R., & Alzahrani, S. [2023]. Effects of different LED spectra and UV-B exposure on growth and phytochemical accumulation in red and green lettuce cultivars. Plants, 12[3], 463.

Aydin, R. [2023]. Hydroponics and urban agriculture: Redefining food production in cities. African Journal of Food Science and Technology, 14[12].

Bamidele Ogunlade, C., & Ebenehi Enemaku, L. [s.f.]. Hydroponic farming: A panacea for climate change impacts on food security in Nigeria. The Federal Polytechnic.

Bantis, F., & Koukounaras, A. [2023]. Impact of Light on Horticultural Crops. Agriculture, 13[828].

Bayat, Leyla & Arab, Mostafa & Aliniaeifard, Sasan & Seif, Mehdi & Lastochkina, Oksana & Li, Tao. [2018]. Effects of growth under different light spectra on the subsequent high light tolerance in rose plants. AoB PLANTS. 10.

Bian, Zhonghua, Cheng, Ruifeng, Wang, Yu, Yang, Qichang, Lu, Chungui, Effect of green light on nitrate reduction and edible quality of hydroponically grown lettuce [Lactuca sativa L.] under short-term continuous light from red and blue light-emitting diodes. Environmental and Experimental Botany

Budavári, N., Pék, Z., Helyes, L., Takács, S., & Nemeskéri, E. [2024]. An overview on the use of artificial lighting for sustainable lettuce and microgreens production in an indoor vertical farming system. Horticulturae, 10[9], 938.

Juárez-Balderas, Mario Alberto, Daniel-Eufracio, América Abigail, Araiz-Aguilar, Gustavo Rafael and Villaseñor-Aguilar, Marcos Jesús. [2025]. Evaluation of LED Systems for controlled spectral lighting in indoor hydroponic cultivation. Journal of Technology and Innovation. 12[30]1-15: e71230115
https://doi.org/10.35429/JTI.2025.12.30.7.1.15

Catota-Ocapana, P., Minaya-Andino, C., Astudillo, P., & Pichoasamin, D. [2024]. Smart control models used for nutrient management in hydroponic crops: a systematic review. IEEE Access

Chen, X., Guo, W., Xue, X., Wang, L., & Qiao, X. [2021]. Light quality regulates plant architecture, biomass accumulation, and energy-use efficiency in hydroponic lettuce. Scientific Reports, 11, 8374.

Chutimanukul, P., Wanichananan, P. Janta, S. et al. [2022]. The influence of different light spectra on physiological responses, antioxidant capacity and chemical compositions in two holy basil cultivars. Scientific Reports.

Fisher, P. [2022, noviembre 21]. Fixed vs. dynamic lighting for indoor hydroponic lettuce. Greenhouse Management.

Gutiérrez León, E., Montiel Arguijo, J. E., Carreto Arellano, C., & Menchaca García, F. R. [2019]. Propuesta de sistema de gestión inteligente basado en IoT para hidroponia. Research in Computing Science, 148[10], 219–233

Hadj Abdelkader, Oussama & Bouzebiba, Hadjer & Pena, Danilo & Aguiar, A. Pedro. [2023]. Energy-Efficient IoT-Based Light Control System in Smart Indoor Agriculture. Sensors. 23.

Johkan, M., Shoji, K., Goto, F., Hashida, S. N., & Yoshihara, T. [2010]. Blue light-emitting diode light irradiation of seedlings improves seedling quality and growth after transplanting in Lactuca sativa L. HortScience, 45[12], 1809–1814.

Kharraz, N., Revoly, A., & Szabó, I. [2025]. IoT-Based Adaptive Lighting Framework for Optimizing Energy Efficiency and Crop Yield in Indoor Farming. *Journal of Sensor and Actuator Networks*, *14*[3], 59.

Kelly, Nathan & Choe, Daegeun & Meng, Qingwu & Runkle, Erik. [2020]. Promotion of lettuce growth under an increasing daily light integral depends on the combination of the photosynthetic photon flux density and photoperiod. Scientia Horticulturae. 272.

Kozai, T. [2018]. Smart Plant Factory the Next Generation Indoor Vertical Farms: The Next Generation Indoor Vertical Farms.

Kuankid, S., & Aurasapon, A. [2022]. The effect of LED lighting on lettuce growth in a vertical IoT based indoor hydroponic system. International Journal of Online Engineering, 18[7], Artículo 25467.

Lee, M. J., Park, S. Y., & Oh, M. M. [2015]. Growth and cell division of lettuce plants under various ratios of red to far-red light-emitting diodes. Horticulture Environment and Biotechnology, 56[2], 186–194.

Legendre, J. M., & van Iersel, M. W. [2021]. Far-red light enhances growth of lettuce by increasing radiation capture efficiency. Plants, 10[1], 166.

Li, Y., Xin, G., Shi, Q., Yang, F., & Wei, M. [2023]. Response of photomorphogenesis and photosynthetic properties of sweet pepper seedlings exposed to mixed red and blue light. Frontiers in Plant Science, 13, Artículo 984051.

Marondedze, Claudius & Liu, Xinyun & Huang, Shihui & Wong, Cynthia & Zhou, Xuan & Pan, Xutong & An, Huiting & Xu, Nuo & Tian, Xuechen & Wong, Aloysius. [2018]. Towards a tailored indoor horticulture: a functional genomics guided phenotypic approach. Horticulture Research. 5. 68. 10.1038/s41438-018-0065-7.

Matysiak, B., Kowalska, I., & Janas, R. [2021]. The impact of different light spectra on the growth and nutritional quality of lettuce [Lactuca sativa L.] in hydroponic cultivation. Agriculture, 11[11], 1133.

Mena Amado, D. J. [s.f. 2018]. Sistema IoT para el monitoreo y control de fuentes de luz artificial aplicado a la agricultura de precisión [Proyecto de grado, Universidad Distrital Francisco José de Caldas]. Facultad de Ingeniería, Proyecto Curricular de Ingeniería Electrónica.

Mohamed, A. H., Latif, H. H. A., & Ali, A. M. [2021]. Impact of spectral composition of LED light on antioxidant properties and growth of Lactuca sativa. Plants, 10[10], 2162.

Motogaito, A., Hashimoto, N., Hiramatsu, K. and Murakami, K. [2017] Study of Plant Cultivation Using a Light-Emitting Diode Illumination System to Control the Spectral Irradiance Distribution. Optics and Photonics Journal, 7, 101-108.

Juárez-Balderas, Mario Alberto, Daniel-Eufracio, América Abigail, Araiz-Aguilar, Gustavo Rafael and Villaseñor-Aguilar, Marcos Jesús. [2025]. Evaluation of LED Systems for controlled spectral lighting in indoor hydroponic cultivation. Journal of Technology and Innovation. 12[30]1-15: e71230115
https://doi.org/10.35429/JTI.2025.12.30.7.1.15

Naim Khalid, S. M. [2020]. Crop production manual: a guide to fruit and vegetable production in the Federated States of Micronesia.

Naznin, M. T., Lefsrud, M., Gravel, V., & Azad, M. O. K. [2019]. Blue light added with red LEDs enhance growth characteristics and total phenolic content of lettuce [Lactuca sativa L.]. Plants, 8[4], 93.

Oh, J. M., Kang, H. J., & Yang, B. D. [2015]. A PWM phase-shift circuit using an RC delay for multiple LED driver ICs. Journal of Semiconductor Technology and Science, 15[4], 484–492.

Palmer, S., & van Iersel, M. W. [2020]. Increasing growth of lettuce and mizuna under sole-source LED lighting using longer photoperiods with the same daily light integral. Agronomy, 10[11], 1722.

Paradiso, Roberta & Proietti, Simona. [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.

Pennisi, G., Takagaki, M., & van Iersel, M. W. [2019]. Optimal red:blue ratio in LED lighting for plant growth and energy use efficiency in lettuce. Scientific Reports, 9, 14127.

Priya, G. Lakshmi & Baskar, Chanthini & Deshmane, Sanket & Adithya, C & Das, Souranil. [2023]. Revolutionizing Holy-Basil Cultivation With AI-Enabled Hydroponics System. IEEE Access. PP. 1-1..

Putra, S. D., Heriansyah, E. F. C., Anggriani, K., & Jaya, M. H. I. S. [2024]. Development of smart hydroponics system using AI-based sensing. Journal Infotel, 16[3], 1–12

Regmi, A., Rueda-Kunz, D., Liu, H., Trevino, J., Kathi, S., & Simpson, C. [2024]. Comparing resource use efficiencies in hydroponic and aeroponic production systems. Technology in Horticulture, 4[1], Artículo 0002.

Reyes Yanes, Abraham & Abbasi, Rabiya & Martínez, Pablo & Ahmad, Dr Rafiq. [2022]. Digital Twinning of Hydroponic Grow Beds in Intelligent Aquaponic Systems. Sensors. 22.

Semenova, Natalya & Proshkin, Yuri & Smirnov, Alexander & Dorokhov, Alexey & Ivanitskikh, Alina & Burynin, Dmitry & Dorokhov, Artem & Uyutova, Nadezhda & Chilingaryan, Narek. [2023]. The Influence of the Spectral Composition and Light Intensity on the Morphological and Biochemical Parameters of Spinach [Spinacia oleracea L.] in Vertical Farming. Horticulturae. 9. 1130.

Shareef, Umar & Rehman, Ateeq & Ahmad, Dr Rafiq. [2024]. A Systematic Literature Review on Parameters Optimization for Smart Hydroponic Systems. AI. 5. 1517-1533.

Singh, D., Basu, C., Meinhardt-Wollweber, M., & Roth, B. [2015]. LEDs for energy efficient greenhouse lighting. Renewable and Sustainable Energy Reviews, 49, 139–147.

Soufi, H. R., Roosta, H. R., & Hamidpour, M. [2023]. The plant growth, water and electricity consumption, and nutrients uptake are influenced by different light spectra and nutrition of lettuce. Scientific Reports, 13, Artículo 48284.

Stevens, J. D., Murray, D., Diepeveen, D., & Toohey, D. [2023]. Development and Testing of an IoT Spectroscopic Nutrient Monitoring System for Use in Micro Indoor Smart Hydroponics. Horticulturae, 9[2], 185.

Taha, M. F., ElManawy, A. I., Alshallash, K. S., ElMasry, G., Alharbi, K., Zhou, L., ... & Qiu, Z. [2022]. Using Machine Learning for Nutrient Content Detection of Aquaponics-Grown Plants Based on Spectral Data. Sustainability, 14[19], 12318

Tavares, P. & Guimaraes, I. & Braga, Henrique & Bender, V. C. & Almeida, Pedro. [2017]. LED system with independent red and blue channels employing radiant flux estimation and indirect flux control for greenhouse hop cultivation. 1-9.

Teo, E. P., Chan, K. Y., Mokhtar, S. M., & Lee, C. L. [2024]. Effect of LED wavelength and power on the hydroponic indoor vegetable farming. Universal Journal of Agricultural Research, 12[1], 41–50.

Thi Phuong Dung, Nguyen & Tran, T.T.H. & Nguyen, Q.T.. [2019]. Effects of light intensity on the growth, photosynthesis and leaf microstructure of hydroponic cultivated spinach [Spinacia oleracea L.] under a combination of red and blue LEDs in house. International Journal of Agricultural Technology. 15. 75-90.

Tiago Queiroz, A., Lopes, R. S., Fortes, M. Z., Tomaz, R. C., Ferreira Beaklini, A. C., Marcos, A., Pereira, E., Soares Moreira, B., Borba, C., & Cavalcanti Tomáz, R. [2019]. Efficiency evaluation in public lighting by using LED and HPS technologies. International Journal of Energy Science and Engineering, 5[1], 12–21.

Van Brenk, Courbier S, Kleijweg CL, Verdonk JC, Marcelis LFM. Paradise by the far-red light: Far-red and red:blue ratios independently affect yield, pigments, and carbohydrate production in lettuce, Lactuca sativa. Front Plant Sci. 2024

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Juárez-Balderas, Mario Alberto, Daniel-Eufracio, América Abigail, Araiz-Aguilar, Gustavo Rafael and Villaseñor-Aguilar, Marcos Jesús. [2025]. Evaluation of LED Systems for controlled spectral lighting in indoor hydroponic cultivation. Journal of Technology and Innovation. 12[30]1-15: e71230115
https://doi.org/10.35429/JTI.2025.12.30.7.1.15