**Effect of Different Wavelengths on The Production of Lettuce Under Solar-Powered Hydroponic System**

**ABSTRACT**

The increasing demand for sustainable agricultural practices has suggested the need for innovative approaches like solar-powered hydroponic systems integrated with LED lighting. The objective of the study is to evaluate the effects of different red and blue LED light combinations on qualitative and quantitative parameters of lettuce and to assess the performance of solar-powered hydroponic systems in controlled environments. This study focuses on optimising lettuce cultivation at College of Agricultural Engineering and Technology, Godhra, Gujarat, India, by examining the impact of varying red and blue LED light spectra on growth and nutritional quality from August 2024 to February 2025. Four treatments were compared: T1 (50% Red - 50% Blue LED), T2 (25% Red - 75% Blue LED), T3 (75% Red - 25% Blue LED), and a control group grown under natural daylight with controlled monitoring of environmental and nutrient parameters. The concentration of phenolic compounds, important antioxidants in lettuce, was influenced by the light treatments. The T2 treatment (25% Red - 75% Blue LED) resulted in the highest average phenol content of 0.68%. The concentration of total soluble sugars, contributing to the sweetness of lettuce, varied among the treatments. The T3 treatment (75% Red - 25% Blue LED) exhibited the highest average total soluble sugar content at 5.5%. Ascorbic acid (Vitamin C) content, a crucial nutritional quality indicator, was significantly influenced by the LED treatments. The T2 treatment (25% Red - 75% Blue LED) resulted in the highest average ascorbic acid level at 15.4 mg/100g. The percentage of protein in the harvested lettuce varied significantly across the treatments. The T1 treatment (50% Red - 50% Blue LED) resulted in the highest average protein content of 44.12%, significantly higher than both T2 and T3 (both at 42.28%) and the control group (40.44%). Chlorophyll content, a proxy for photosynthetic capacity, was highest in the T2 treatment (25% Red - 75% Blue LED) with an average of 2.1 mg/g fresh weight. Anthocyanin content, contributing to both the color and antioxidant properties of lettuce, was highest in the T2 treatment (25% Red - 75% Blue LED) with an average of 0.82%. Possible outcomes include optimized lighting configurations for maximizing lettuce yield and nutritional quality, with reduced energy consumption. The findings could promote the widespread adoption of sustainable, energy-efficient hydroponic farming practices to address global food security challenges.

Keywords

*Lettuce cultivation, hydroponics, LED lighting, solar-powered systems, sustainable agriculture, controlled environments, renewable energy, crop optimization*

# INTRODUCTION

The substantial increase in the human population dramatically strains food supplies. Farmers need healthy soil and natural minerals for traditional farming, and production takes a little longer time. The soil-free farming method known as vertical farming requires a small land and consumes a very small amount of water than conventional soil-dependent farming techniques. With modern technologies like hydroponics, aeroponics, and aquaponics, the notion of the vertical farming appears to have a promising future in urban areas where farming land is very expensive and scarce (Rathor et al., 2024). The integration of hydroponics into tropical agricultural systems provides a promising way to address issues including decreasing arable land, unpredictable weather patterns and concerns about food security. The possibilities for hydroponics in tropical nations are evaluated, with a focus on the necessity of technology developments, regulatory assistance and sustainable methods for implementation (Ranade & Chaudhari, 2025). This study aimed to determine the effect of different wavelengths on the production of lettuce under solar powered hydroponic system.

## 1.1 Renewable Energy Sources (RES) & Sustainable Agriculture

RES, comprising biomass, hydropower, geothermal, solar, wind, and marine energy, accounts for 14% of global energy demand. Large-scale hydropower generates 20% of the world's electricity, while wind power thrives in coastal and windy regions. As fossil fuel concerns grow, RES adoption is key to energy security and sustainability (Panwar et al., 2011).

## 1.2 Greenhouse & Polyhouse Farming

Greenhouse farming optimizes plant growth by controlling temperature, humidity, and light, enabling year-round production and resource efficiency. Advanced technologies like automated climate control enhance sustainability (Salazar & Rios, 2005). Polyhouse farming, using plastic-covered frames, integrate IoT and solar energy for smarter, sustainable food production (Preprint et al., 2021).

## 1.3 Hydroponics & Urban Agriculture

Hydroponics, vital for urban agriculture, overcomes land scarcity by enabling soil-less cultivation with efficient resource use. It supports higher yields through vertical farming, precise nutrient management, and automation. Hydroponics reduces chemical use, conserves water, and ensures a year-round food supply (View of Hydroponics, 2021).

## 1.4 Lettuce Cultivation & Light Effects

Lettuce (Lactuca sativa L.) is a nutrient-rich crop thriving in hydroponics and aquaponics. Controlled environments boost growth, reducing harvest time to 30 days (Kovacsne Madar et al., 2019). Light quality influences growth: blue light slows growth but expands leaf area, while red light accelerates it. Red LEDs enhance shade tolerance, photosynthesis, and bioactive compound accumulation (Flores et al., 2022). High red light (>70%) boosts leaf number and petiole size, while blue light enhances antioxidant synthesis, benefiting red-leaved lettuce varieties (Modarelli et al., 2022). Optimizing light wavelengths improves photosynthetic efficiency, yield, and plant quality (Chen et al., 2016; Mohamed et al., 2021).

# REVIEW OF LITERATURE

## 2.1 Genesis and Evolution of Lettuce Cultivation

Lettuce (Lactuca sativa L.) is a nutrient-rich leafy vegetable with high water content (Tripathi et al., 2022). Leaf varieties offer more minerals than iceberg lettuce, while red lettuce is higher in phenolic compounds. Advanced cultivation techniques like hydroponics and optimized lighting improve its nutritional value. Originating from the Mediterranean, lettuce has been cultivated for over 4,500 years (Mou, 2009). It is a major crop worldwide, with China leading production. In the U.S., it is the second most consumed vegetable, with breeding programs enhancing its nutritional quality. Economically, lettuce ranked as the second most valuable vegetable in the U.S. in 2005, with increasing global production driven by improved practices (Still, 2007).

## 2.2 Comparative Study of Hydroponic and Aquaponic Systems for Crop Production

Recent studies highlight the role of solar-powered hydroponic systems in improving energy efficiency and food security (Sidibe et al., 2023; Manalu et al., 2023). IoT-enabled hydroponics optimize energy use and crop monitoring (Orakwue et al., 2022; Wedashwara et al., 2021). Comparative studies show that aquaponics enhances yield while providing additional income from fish production (Tarranum et al., 2020). Nutrient Film Technique (NFT) systems are particularly effective for lettuce growth (Frasetya et al., 2021). Research also emphasizes the importance of nutrient flow rates and automated energy management for optimizing hydroponic crop production (Bosco, 2012; Sarathkumar, 2019).

## 2.3 Study of Lighting Effects on Lettuce

Photoperiod and light spectrum significantly affect lettuce growth. A 24-hour photoperiod maximized biomass (Yudina et al., 2023), while red and blue LED light combinations influenced morphology and yield (Chen et al., 2019). End-of-day light treatments altered fresh mass and antioxidant content, depending on the cultivar (Kovacsne et al., 2019). Optimized LED spectra, particularly deep-red and far-red, improved photosynthesis and nutrient uptake (Pinho et al., 2017; Bian et al., 2016). Studies confirm that dynamic lighting strategies enhance both crop quality and energy efficiency in controlled environments (Saito et al., 2010). Overall, advancements in cultivation methods, hydroponic technologies, and optimized lighting have significantly improved lettuce production, quality, and sustainability.

## 2.4 Genesis and Evolution of Lettuce Cultivation

Lettuce (Lactuca sativa L.) is a widely cultivated leafy vegetable, valued for its high water content (95%) and rich nutritional profile, including fiber, minerals, vitamins, and bioactive compounds (Tripathi et al., 2022). Leaf lettuce varieties are more nutrient-dense than iceberg lettuce, with red lettuce containing higher phenolic compounds and green leaf varieties being richer in vitamin C. Advanced cultivation techniques, such as hydroponics and optimized lighting, enhance its nutrient content and yield.

Lettuce originated in the Mediterranean over 4,500 years ago, with evidence of cultivation found in Egyptian tomb paintings (Mou, 2009). It thrives globally, particularly in temperate and subtropical regions, with China being the largest producer. In the U.S., lettuce ranks as the second most consumed fresh vegetable, with California and Arizona leading production. Efforts in breeding and biotechnology continue to improve its nutritional quality to meet growing health-conscious demands. Economically, lettuce was the second most valuable vegetable in the U.S. in 2005, generating $1.98 billion, with global production expanding 2.7 times since 1980 due to improved agricultural practices (Still, 2007).

## 2.5 Comparative Study of Hydroponic and Aquaponic Systems for Crop Production

Hydroponic systems have evolved with the integration of renewable energy, automation, and IoT technologies to enhance efficiency and sustainability. Solar-powered hydroponic systems have been developed to reduce energy costs and provide off-grid solutions for remote farming (Sidibe et al., 2023; Manalu et al., 2023). IoT-enabled hydroponic setups allow real-time monitoring of environmental conditions, ensuring optimal crop growth even under fluctuating power availability (Orakwue et al., 2022; Wedashwara et al., 2021).

Comparative studies indicate that aquaponic systems, which combine fish farming with hydroponics, enhance crop yield while offering additional income sources (Tarranum et al., 2020). The Nutrient Film Technique (NFT) has been identified as one of the most efficient hydroponic methods, increasing lettuce yields by 6–10% due to improved nutrient uptake (Frasetya et al., 2021). Research also emphasizes that optimizing nutrient flow rates and maintaining ideal ionic concentrations in hydroponic solutions significantly improve fresh mass accumulation and plant health (Bosco, 2012; Sarathkumar, 2019). The integration of renewable energy and automation further supports the transition toward sustainable, resource-efficient agricultural systems.

## 2.6 Study of Lighting Effects on Lettuce

Light quality, intensity, and photoperiod play a crucial role in lettuce growth and productivity. A 24-hour photoperiod was found to maximize biomass and dry weight, suggesting that continuous lighting could enhance production in controlled environments (Yudina et al., 2023). The spectral composition of light also influences lettuce morphology and nutrient content. Red light promotes compact growth, while blue light thickens leaves; however, excessive red light can cause petiole distortion (Chen et al., 2019).

End-of-day (EOD) light treatments, including blue, far-red, and ultraviolet-A (UV-A) light, impact fresh yield and antioxidant levels, with effects varying between cultivars (Kovacsne et al., 2019). Optimized LED spectra, particularly deep-red and far-red light, improve photosynthesis efficiency and nutrient absorption, making LED technology more effective than traditional lighting systems (Pinho et al., 2017; Bian et al., 2016). Dynamic lighting strategies that alternate red and blue light maximize lettuce growth while maintaining an ideal plant structure (Saito et al., 2010). Overall, advancements in cultivation techniques, hydroponic innovations, and controlled lighting environments have significantly enhanced lettuce production, improving both yield and quality while promoting sustainable agricultural practices.

## MATERIALS AND METHODS

**3.1 Experimental Design**

A complete randomized factorial design was employed to investigate the impact of varying red and blue LED light ratios on lettuce cultivation. The experiment was conducted in a controlled greenhouse environment equipped with a solar-powered hydroponic system using the Nutrient Film Technique (NFT). The purpose of the experiment was to determine how different red-to-blue LED light ratios influence plant growth, yield, and nutritional content.

## Treatment Groups

The experiment included three LED light treatments and a control group:

1. **T1:** 50% red - 50% blue LED
2. **T2:** 25% red - 75% blue LED
3. **T3:** 75% red - 25% blue LED
4. **Control:** Natural daylight (NDL)

Each treatment was applied to separate lettuce beds, ensuring uniform exposure to the designated lighting conditions.

## System Specifications

* + **Hydroponic System:** Nutrient Film Technique (NFT) setup powered by solar panels.
	+ **LED Lights:** Adjustable wavelength LEDs covering the spectrum from 430 nm (blue) to 680 nm (red).

## Environmental Conditions:

* + - Temperature: Maintained between 20-24°C
		- Relative Humidity: 65-70%
		- pH: Maintained between 5.5-6.5
		- Electrical Conductivity (EC): 1-1.5 mS/cm
	+ **Nutrient Solution:** Hoagland solution, adjusted periodically for pH and EC to maintain optimal nutrient availability.

## 3.2 Data Collection & Growth Metrics

* Days to first harvest.
* Leaf area (cm²) was measured using a digital planimeter.
* Root biomass (wet and dry weights in grams).
* Yield per plant (g) and per square meter (kg/m²).

## Nutritional Analysis

* **Phenol Content (%):** Determined using the Folin-Ciocalteau reagent.
* **Ascorbic Acid (%):** Measured through titrimetric analysis.
* **Protein Content (%):** Analyzed using the Micro-Kjeldahl method.
* **Chlorophyll Content (mg/g fresh weight):** Quantified spectrophotometrically at wavelengths of 645 nm and 663 nm.
* **Anthocyanin Content (mg/100 g):** Extracted using ethanolic-hydrochloric method and measured spectrophotometrically.

# 4. RESULTS AND DISCUSSION

This section presents the findings of the experiment evaluating the impact of different supplemental LED lighting spectra on the growth, yield, nutritional composition, and moisture content of hydroponically grown lettuce. Four treatments were compared: T1 (50% Red - 50% Blue LED), T2 (25% Red - 75% Blue LED), T3 (75% Red - 25% Blue LED), and a control group grown under natural daylight.

## 4.1 Growth Parameters:

## 4.1.1 Days Until the First Cutting

The lettuce plants across all treatment groups, including the control, reached harvest maturity and were ready for the first cutting at a consistent 45-day post-transplanting. This uniformity in the developmental timeline suggests that the supplemental LED lighting treatments, despite their variations in spectra, did not significantly accelerate or delay the maturity time compared to natural daylight conditions. The consistent maturity time also implies that the hydroponic system provided stable and adequate environmental conditions for growth across all treatments. This finding indicates that the primary influence of LED lighting was likely on the quality and yield attributes rather than the fundamental growth duration.

## 4.1.2 Leaf Area (cm²)

Significant differences in leaf area were observed among the treatments. The T1 treatment (50% Red - 50% Blue LED) resulted in an average leaf area of 165 cm², indicating a balanced promotion of vegetative growth. The T3 treatment (75% Red - 25% Blue LED) produced the largest leaves, averaging 180 cm², but this increase was noted to be associated with excessive stem elongation and potentially weaker plant structure (as discussed further in subsequent sections). Plants under the T2 treatment (25% Red - 75% Blue LED) exhibited an average leaf area of 150 cm², while the control group grown under natural daylight had the smallest average leaf area of 130 cm². These results underscore the critical role of the light spectrum in influencing leaf development, with a balanced red-to-blue light ratio (as in T1) appearing optimal for robust leaf expansion without compromising plant morphology.

## 4.1.3 Root Weight and Dry Root Biomass (g)

Root development, a key factor in nutrient and water uptake, varied across the treatments. The T1 treatment (50% Red - 50% Blue LED) demonstrated the most substantial root development, recording the highest average root fresh weight of 2.5 g per plant and a dry root biomass of 0.6 g. This indicates the development of strong and healthy root systems under this specific light spectrum. Treatments T2 and T3 showed slightly reduced root performance, with average fresh root weights of 2.3 g and 2.2 g, and dry biomass values of 0.55 g and 0.5 g, respectively. The control group exhibited the least developed root systems, with an average fresh root weight of 1.8 g and a dry biomass of 0.45 g. The superior root development observed under T1 conditions likely contributed to enhanced water and nutrient absorption, positively impacting overall plant growth and vigor.

## 4.1.4 Yield (g/plant and kg/m²)

The primary measure of productivity, yield, was significantly influenced by the supplemental LED lighting. The T1 treatment (50% Red - 50% Blue LED) achieved a notable yield of 140 g per plant, translating to an estimated 5.5 kg/m² in a controlled environment setting. This demonstrates the efficacy of this balanced light spectrum in enhancing lettuce productivity while maintaining overall plant robustness. The T3 treatment (75% Red - 25% Blue LED) yielded slightly higher at 150 g per plant (6 kg/m²); however, as previously mentioned, this was accompanied by undesirable excessive leaf elongation, potentially impacting overall quality and shelf life. The T2 treatment (25% Red - 75% Blue LED) resulted in a yield of 135 g per plant (5.2 kg/m²), and the control group under natural daylight produced the lowest yield at 120 g per plant (4.8 kg/m²). These findings highlight that while a higher red-light percentage can potentially increase biomass, a balanced red-to-blue ratio, as in T1, appears optimal for achieving a high yield without compromising other crucial plant characteristics.

## 4.1.5 Moisture Content (%)

The moisture content of the harvested lettuce, an important factor for freshness and shelf life, varied among the treatments. The T1 treatment (50% Red - 50% Blue LED) maintained an optimal average moisture content of 89%, striking a balance between crispness and reduced water loss, potentially contributing to a longer shelf life. The T2 treatment (25% Red - 75% Blue LED) exhibited the highest average moisture content at 91%, which, while indicating high water content at harvest, could potentially lead to a shorter shelf life due to increased susceptibility to spoilage. The T3 treatment (75% Red - 25% Blue LED) and the control group showed lower average moisture content values of 87% and 85%, respectively. These results suggest that the balanced light spectrum of T1 not only supports ideal hydration during growth but may also contribute to improved post-harvest quality.

## 4.2 Nutritional Analysis

## 4.2.1 Phenol Content (%)

The concentration of phenolic compounds, important antioxidants in lettuce, was influenced by the light treatments. The T2 treatment (25% Red - 75% Blue LED) resulted in the highest average phenol content of 0.68%. The T1 treatment (50% Red - 50% Blue LED) showed a slightly lower but still substantial phenol content of 0.64%, indicating a good balance between nutritional benefits and overall plant health. The T3 treatment (75% Red - 25% Blue LED) and the control group exhibited lower average phenol content values of 0.60% and 0.55%, respectively. The relatively high phenol content in T1 suggests that a moderate proportion of blue light is sufficient to stimulate the production of these beneficial secondary metabolites without potentially inducing stress that could negatively impact growth.

## 4.2.2 Acidity (%)

Acidity, a contributing factor to the taste profile of lettuce, showed relatively minor variations across the treatments. Both the T1 (50% Red - 50% Blue LED) and T2 (25% Red - 75% Blue LED) treatments recorded an average acidity of 0.34%, suggesting a consistent and potentially desirable taste. The T3 treatment (75% Red - 25% Blue LED) had a slightly lower average acidity of 0.32%, while the control group exhibited the lowest average acidity at 0.30%. These results indicate that the supplemental LED lighting, particularly the balanced and blue-light-rich spectra, can help maintain a consistent acidity level that contributes to the sensory attributes of the lettuce.

## 4.2.3 Total Soluble Sugar (%)

The concentration of total soluble sugars, contributing to the sweetness of lettuce, varied among the treatments. The T3 treatment (75% Red - 25% Blue LED) exhibited the highest average total soluble sugar content at 5.5%. However, as noted earlier, this was associated with undesirable morphological changes. The T1 treatment (50% Red - 50% Blue LED) showed a high average sugar concentration of 5.2%, indicating a favorable balance between sweetness and overall plant quality. The T2 treatment (25% Red - 75% Blue LED) and the control group presented lower average sugar levels of 4.8% and 4.5%, respectively. These findings emphasize the need for a carefully balanced light spectrum to enhance the sweetness of lettuce without compromising its structural integrity.

## 4.2.4 Ascorbic Acid (Vitamin C, mg/100g)

Ascorbic acid (Vitamin C) content, a crucial nutritional quality indicator, was significantly influenced by the LED treatments. The T2 treatment (25% Red - 75% Blue LED) resulted in the highest average ascorbic acid level at 15.4 mg/100g. The T1 treatment (50% Red - 50% Blue LED) also demonstrated a high average ascorbic acid content of 14.8 mg/100g, outperforming the T3 treatment (14.2 mg/100g) and the control group (13.5 mg/100g). While T2 showed the highest Vitamin C, its performance in other growth and quality parameters was not consistently superior to T1, highlighting the balanced benefits offered by the 50% Red - 50% Blue LED spectrum.

## 4.2.5 Protein Content (%)

The percentage of protein in the harvested lettuce varied significantly across the treatments. The T1 treatment (50% Red - 50% Blue LED) resulted in the highest average protein content of 44.12%, significantly higher than both T2 and T3 (both at 42.28%) and the control group (40.44%). The increased protein content under the balanced light conditions of T1 is likely attributable to enhanced nitrogen uptake and assimilation, crucial processes for producing nutritionally rich lettuce.

## 4.2.6 Total Chlorophyll (mg/g fresh weight)

Chlorophyll content, a proxy for photosynthetic capacity, was highest in the T2 treatment (25% Red - 75% Blue LED) with an average of 2.1 mg/g fresh weight. The T1 treatment (50% Red - 50% Blue LED) also exhibited a high average chlorophyll content of 1.9 mg/g. The T3 treatment (75% Red - 25% Blue LED) recorded an average of 1.8 mg/g, while the control group showed the lowest average chlorophyll content at 1.6 mg/g. These findings reinforce the effectiveness of supplemental LED lighting, particularly spectra with a higher proportion of blue light (T1 and T2), in promoting chlorophyll synthesis and potentially enhancing photosynthetic efficiency.

## 4.2.7 Anthocyanin Content (%)

Anthocyanin content, contributing to both the color and antioxidant properties of lettuce, was highest in the T2 treatment (25% Red - 75% Blue LED) with an average of 0.82%. The T1 treatment (50% Red - 50% Blue LED) also showed a high average anthocyanin content of 0.78%. The T3 treatment (75% Red - 25% Blue LED) recorded an average of 0.74%, while the control group had the lowest average anthocyanin content at 0.70%. These results affirm that supplemental LED lighting with a balanced or higher proportion of blue light can enhance the production of these beneficial pigments, improving both the aesthetic appeal and nutritional value of the lettuce.

# 5. CONCLUSION

The results of the first trial demonstrate that the T1 treatment (50% Red - 50% Blue LED) offers the best overall performance in terms of yield, plant vigor, and nutritional quality. While T3 maximized yield, it also led to excessive elongation, compromising plant integrity. T2 excelled in phenol content but delivered lower yields. Therefore, T1 is the optimal choice for cultivating lettuce in a solar-powered hydroponic system, providing a balanced approach to

growth, yield, and quality. The findings support the integration of a balanced red-blue LED spectrum in hydroponic systems to enhance both the productivity and marketability of lettuce.

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# REFERENCE:

Baakrishna Bhat Jayanth Gowda R, Mohammed Umair S, & M. Y. (2022). Fabrication of Solar Operated Smart Hydrophonics System For Fodder Feed Growing. 45th Series Student Project Programme. https://doi.org/10.3791/54317

Bian, Z.-H., Cheng, R.-F., Yang, Q.-C., Wang, J., & Lu, C. (2016). Continuous Light from Red, Blue, and Green Light-emitting Diodes Reduces Nitrate Content and Enhances Phytochemical Concentrations and Antioxidant Capacity in Lettuce. J. Amer. Soc. Hort. Sci., 141(2).

Bosco. (2012). HB 30\_3.

Chen, X. L., Wang, L. C., Li, T., Yang, Q. C., & Guo, W. Z. (2019). Sugar accumulation and growth of lettuce exposed to different lighting modes of red and blue LED light. Scientific Reports, 9(1). https://doi.org/10.1038/s41598-019-43498-8

Chen, X. L., Xue, X. Z., Zhang, G. W. Z., Wang, L. C., & Qiao, X. J. (2016). Growth and nutritional properties of lettuce affected by mixed irradiation of white and supplemental light provided by light-emitting diode. Scientia Horticulturae, 200, 111–118. https://doi.org/10.1016/j.scienta.2016.01.007

Delaide, B., Goddek, S., Gott, J., Soyeurt, H., & Jijakli, M. H. (2016). Lettuce (Lactuca sativa L. var. Sucrine) growth performance in complemented aquaponic solution outperforms hydroponics. Water (Switzerland), 8(10). https://doi.org/10.3390/w8100467

Flores, M., Urrestarazu, M., Amorós, A., & Escalona, V. (2022). High intensity and red enriched LED lights increased the growth of lettuce and endive. Italian Journal of Agronomy,

17(1). https://doi.org/10.4081/ija.2021.1915

Frasetya, B., Harisman, K., & Ramdaniah, N. A. H. (2021). The effect of hydroponics systems on the growth of lettuce. IOP Conference Series: Materials Science and Engineering, 1098(4), 042115. https://doi.org/10.1088/1757-899x/1098/4/042115

Gent, M. P. N. (2012). Composition of hydroponic lettuce: Effect of time of day, plant size, and season. Journal of the Science of Food and Agriculture, 92(3), 542–550. https://doi.org/10.1002/jsfa.4604

Gent, M. P. N. (2017). Factors affecting relative growth rate of lettuce and spinach in hydroponics in a greenhouse. HortScience, 52(12), 1742–1747. https://doi.org/10.21273/HORTSCI12477-17

Hariono, T., Gofar, M. A., & Hasbullah, K. A. W. (2021). Implementation of Solar Cells for Energy Sources in Hydroponic Automation Systems. 1(1), 23–27.

Kovácsné Madar, Á., Rubóczki, T., & Takácsné Hájos, M. (2019). Lettuce production in aquaponic and hydroponic systems. Acta Universitatis Sapientiae, Agriculture and Environment, 11(1), 51–59. https://doi.org/10.2478/ausae-2019-0005

Loomis, J., DiLeonardo, M., Al Charif, K., & Walker, J. (2021). LeafAlone Hydroponics System.

Manju, H. M., Singh, M., Yadav, K. K., & Bhakar, S. R. (2020). Development of Solar Operated Hydroponic Fodder Production System. International Journal of Current Microbiology and Applied Sciences, 9(11), 2936–2942. https://doi.org/10.20546/ijcmas.2020.911.357

Modarelli, G. C., Paradiso, R., Arena, C., De Pascale, S., & Van Labeke, M. C. (2022). High Light Intensity from Blue-Red LEDs Enhance Photosynthetic Performance, Plant Growth, and Optical Properties of Red Lettuce in Controlled Environment. Horticulturae, 8(2). https://doi.org/10.3390/horticulturae8020114

Orakwue, S. I., Al-Khafaji, H. M. R., Ikenyiri, V. C., & Godson, V. C. (2022). Solar Powered Automated Hydroponic Farming System with IoT Feedback. Journal of Information Technology Management, 14(3), 26–38. https://doi.org/10.22059/jitm.2022.87261

Paz, M., Fisher, P. R., & Gómez, C. (2019). Minimum Light Requirements for Indoor Gardening of Lettuce. Urban Agriculture and Regional Food Systems, 4(1), 1–10. https://doi.org/10.2134/urbanag2019.03.0001

Saito, Y., Shimizu, H., Nakashima, H., Miyasaka, J., & Ohdo, K. (2010). The effect of light quality on growth of lettuce. IFAC Proceedings Volumes, 3(PART 1). https://doi.org/10.3182/20101206-3-jp-3009.00052

Sidibé, A., et al. (2023). Design and Implementation of Energy-Water Nexus Management in a Solar-Powered NFT Hydroponic System. Universal Journal of Agricultural Research, 11(3), 664–672. https://doi.org/10.13189/ujar.2023.110316

Yudina, L., et al. (2023). Effect of Duration of LED Lighting on Growth, Photosynthesis and Respiration in Lettuce. Plants, 12(3). <https://doi.org/10.3390/plants12030442>

Rathor, A. S., Choudhury, S., Sharma, A., Nautiyal, P., & Shah, G. (2024). Empowering vertical farming through IoT and AI-Driven technologies: A comprehensive review. Heliyon. Volume 10, Issue 15, e34998

Ranade, Y., & Chaudhari, N. (2025). Integrating hydroponics into tropical agricultural systems: implications for food security. The Journal of Horticultural Science and Biotechnology, 1-8.