



Growth performance of green cos lettuce under differential light intensities in controlled vertical hydroponic cultivation

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Abstract

The increasing popularity of closed-system hydroponic cultivation has led to the need for optimizing environmental conditions to achieve uniform and high-quality crop production. One of the most important factors affecting plant growth is light intensity, which directly influences photosynthesis and nutrient accumulation. This study aimed to investigate the growth response of Green Cos lettuce (Caesar) under different light intensities in a controlled hydroponic environment and to record the growth parameters of the plants. The experimental procedure began with seed germination and seedling development, which took 28 days before transplanting into cultivation layers. The system consisted of three layers with identical environmental conditions, including nutrient solution pH, electrical conductivity (EC), air temperature, water temperature, relative humidity, and photoperiod, all monitored by sensors. The only difference among the layers was the number of LED grow lights used. Layer 1 was equipped with two lights, Layer 2 with three lights, and Layer 3 with four lights. Each light was an LED Grow Light Eco 18W (Flux PPF: PAR + PPF (400–800 nm) 27 $\mu\text{mol/s}$). Data was collected every five days from September 15, 2025, to October 15, 2025, for a total of 31 days, resulting in seven measurement intervals. Growth parameters recorded included leaf number, leaf size, plant height, and canopy width, as well as leaf color and appearance. The results showed that light intensity had a significant effect on the growth of Green Cos lettuce (Caesar). Plants grown in Layer 3, which received the highest light intensity, exhibited the best growth performance, with larger and longer leaves, uniform plant structure, and a healthy overall appearance. The average canopy width at maturity was 32.7 ± 1.98 cm for Layer 3, 29.0 ± 1.07 cm for Layer 2, and 23.8 ± 1.05 cm for Layer 1. The canopy width of plants in Layer 3 was 12.8% and 37.4% greater than those in Layers 2 and 1, respectively, while Layer 2 showed a 21.9% increase compared to Layer 1. The percentage increase of canopy width was calculated using the formula $[\text{Greater canopy width} - \text{Smaller canopy width}] / \text{Smaller canopy width} \times 100$. However, in all layers, the leaf characteristics are not very uniform; some leaves are curled and wrinkled, but most are complete. These findings indicate that optimizing light intensity plays a crucial role in enhancing the growth and quality of hydroponically grown Green Cos lettuce. The optimal light intensity for Green Cos (Caesar) in this study was $150 \mu\text{mol/m}^2/\text{s}$, achieved using four LED grow lights.

Keywords: Green cos lettuce, Hydroponic system, Light intensity, Growth response, Controlled environment

1. Introduction

Hydroponic cultivation has gained increasing global attention in recent years due to its potential to produce high-quality vegetables in a controlled environment while using resources efficiently [1]. Unlike conventional soil-based cultivation, hydroponic systems enable precise management of water, nutrients, and environmental factors such as temperature, humidity, and light, minimizing the risk of soil-borne diseases, pesticide residues, and nutrient loss [2-3]. In addition, hydroponics allows for year-round production in limited spaces, which is particularly beneficial in urban agriculture and vertical farming. As food demand continues to increase and arable land decreases, hydroponic production systems are becoming an essential component of sustainable agriculture [4]. However, achieving uniform growth and high crop quality remains a key challenge, particularly in multi-layer cultivation systems, where variations in light distribution, temperature gradients, and airflow between upper and lower layers can lead to inconsistent growth performance [5]. These differences may result in uneven canopy development, inconsistent leaf coloration, and variable marketable yield, all of which can affect the overall productivity and profitability of hydroponic operations. Consequently, understanding how to optimize environmental parameters, especially light intensity is crucial for improving both plant performance and energy efficiency [6-7]. Green Cos lettuce (Caesar) is one of the most popular leafy vegetables in hydroponic production due to its rapid growth, crisp texture, and high market demand [2]. It is widely used in salads and fresh markets, making consistent size, color, and leaf quality

important for consumer acceptance. Although several environmental factors such as pH, electrical conductivity (EC), temperature, and humidity can be effectively controlled using sensors and automation systems, light intensity remains a major variable influencing the uniformity and morphology of the crop [5, 8]. In multi-layer hydroponic systems, lower layers often receive less light due to shading from upper tiers, resulting in thinner leaves, reduced canopy width, and lower yield. Addressing this issue through strategic lighting design can significantly enhance overall system performance and commercial value [9].

Light intensity is among the most influential factors regulating plant growth and morphology. It directly affects the photosynthetic rate, carbon assimilation, and chlorophyll content of leaves. Plants use light not only as an energy source but also as an environmental signal influencing physiological processes such as leaf expansion, stem elongation, and biomass allocation [9]. When light intensity is too low, plants exhibit slower growth, elongated stems, and smaller leaves due to insufficient photosynthetic energy. Conversely, excessive light intensity may cause photo-oxidative stress and energy waste, particularly in indoor farming where electricity costs are significant [10]. Therefore, identifying the optimal range of photosynthetic photon flux density (PPFD) for hydroponic crops is essential to balance productivity and energy consumption.

Recent studies have proposed that the optimal daily light integral (DLI) for lettuce ranges between 11 and 18 mol m⁻² d⁻¹, depending on cultivar and growth stage [4]. Hernández-Adasme, et al. [10] found that lettuce exposed to 150–200 μmol m⁻² s⁻¹ PPFD achieved the highest yield and antioxidant activity, while higher intensities did not further improve growth. Similarly, Boros, et al. [7] and Pinho, et al. [11] reported that optimizing both light intensity and spectrum (red-blue ratio or inclusion of far-red light) improved photosynthetic efficiency and leaf uniformity in multi-tier hydroponic systems. These findings emphasize the necessity of customizing lighting strategies according to the vertical layer's position to achieve uniform growth.

Therefore, this study aims to investigate the effects of different light intensities on the growth performance of Green Cos lettuce cultivated in a controlled hydroponic system. The experiment focuses on evaluating how varying light levels across cultivation layers influence morphological characteristics such as leaf number, leaf area, canopy width, and plant height. The findings are expected to provide practical insights for optimizing lighting configurations in vertical hydroponic farms to achieve uniform growth, superior crop quality, and improved resource-use efficiency.

2. Materials and methods

2.1 Three-layer vertical hydroponic system

The three-layer hydroponic lettuce cultivation structure was made of black-painted steel, with a total height of 220 cm, a length of 135 cm, and a width of 80 cm. Within the structure, the third cultivation layer had a height of 48 cm, while the first and second layers each had a height of 44 cm. The steel frames used for construction were 4 cm wide. The components of the cultivation system are shown in Figure 1. This structure was used for growing Green Cos lettuce (Caesar) until the plants reached full growth.



Figure 1 Overview of the three-layer vertical hydroponic system used in the experiment

2.2 Circuit diagram of sensors

Figure 2 shows the circuit diagram of the sensor system, which consists of an LDR (LM393), DHT22 (AM2302), DS18B20, a 16×2 LCD display (1602), Arduino Uno R3 (ATmega328P), and a breadboard. This setup enables the measurement of various environmental parameters and serves as an essential component of the smart hydroponic farming system.

2.3 Data analysis

The experiment was conducted using Green Cos lettuce (Caesar) cultivated in a three-layer recirculating hydroponic system under controlled environmental conditions. Each layer received different light intensities by varying the number of LED grow lights: two lights for Layer 1, three for Layer 2, and four for Layer 3. The light source used was LED Grow Light Eco 18W (Flux PPF: PAR + PPF 400–800 nm, 27 μmol/s), according to the manufacturer's specifications provided by CIVIC AGROTECH CO., LTD.

All layers were maintained under identical environmental conditions, including the pH of the nutrient solution, electrical conductivity (EC), water temperature, air temperature, and relative humidity. These parameters were continuously monitored by sensors and displayed through an Arduino system. The photoperiod was fixed at 12 hours per day.

Each cultivation layer consisted of 7 rows with 6 plants per row, totaling 42 plants per layer. Eighteen plants from the three central rows of each layer were randomly selected for growth measurements to minimize edge effects. Growth parameters recorded included

leaf number, leaf size, leaf characteristics, plant height, canopy width, and leaf color. Measurements were taken every five days, for a total of seven times over a 31-day period, using a ruler for physical dimensions and timers to control the light on/off duration.

Light intensity in each layer was measured as Photosynthetic Photon Flux Density (PPFD, $\mu\text{mol}/\text{m}^2/\text{s}$) using light sensors. The mean values of all measured growth parameters were calculated, and growth performance among layers was compared using appropriate statistical analysis to determine the effects of light intensity on plant development.

Figure 3 illustrates the growth of Green Cos lettuce (Caesar) across the three cultivation layers at different growth stages under controlled environmental conditions. The main difference among the layers is the varying light intensity received by each layer.

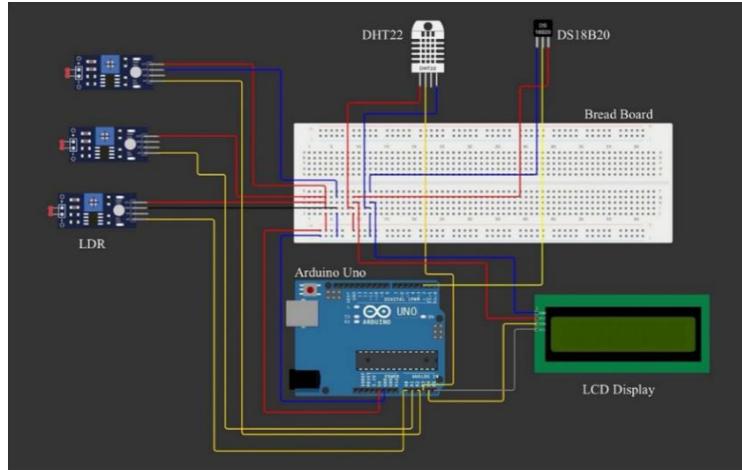


Figure 2 Circuit diagram of sensors used in the vertical hydroponic system



Figure 3 Growth progression of Green Cos Lettuce (Caesar) observed at different cultivation periods

The growth measurements of Green Cos lettuce (Caesar), as shown in Figure 4, included leaf length, leaf width, plant height, and canopy width. For leaf-related measurements, only the middle leaves of each plant were measured, while the oldest and youngest leaves were excluded.



Figure 4 Measurement methods of Green Cos Lettuce (Caesar) growth parameters: (a) leaf length, (b) leaf width, (c) plant height, and (d) canopy width

3. Results and discussion

The experiment investigated the effect of light intensity from LED grow lights on the growth of Green Cos lettuce (Caesar) cultivated in a controlled hydroponic environment. Light intensity served as the independent variable, while the growth performance of Green Cos lettuce was considered the dependent variable. To ensure reliable and consistent results, several environmental factors were kept constant throughout the study. The photoperiod was maintained at 12 hours of light per day. The water temperature was controlled at approximately 23-25°C, while the air temperature was maintained between 24-25°C. Relative humidity was kept within the range of 60–80%. The pH of the nutrient solution was adjusted and stabilized between 5-6.5, and the electrical conductivity (EC) was maintained within 900-1,100 $\mu\text{S}/\text{cm}$. These controlled conditions helped minimize external variations, ensuring that any observed differences in plant growth were primarily due to the variations in light intensity among the cultivation layers.

The growth of Green Cos lettuce (Caesar) was clearly influenced by the light intensity provided in each cultivation layer. Table 1 summarizes the measured growth parameters, including leaf number, leaf length, leaf width, plant height, canopy width, as well as leaf characteristics and color. The corresponding graph illustrates the comparison of canopy width among the layers for each measurement period.

As shown in the Table 1 and Figure 5, plants grown in Layer 3, which received the highest light intensity using four LED Grow Lights Eco (PPFD $\approx 150 \pm 5.48 \mu\text{mol}/\text{m}^2/\text{s}$ and DLI =6.48 $\text{mol}/\text{m}^2/\text{day}$), exhibited the best growth, with larger and longer leaves, taller plants, and wider canopies, although some leaves were slightly twisted and curled. The average canopy width for Layer 3 was $32.7 \pm 1.98 \text{ cm}$. Layer 2 (PPFD $\approx 122 \pm 2.48 \mu\text{mol}/\text{m}^2/\text{s}$ and DLI =5.27 $\text{mol}/\text{m}^2/\text{day}$) showed moderate growth, with some twisted and curled leaves as well, and an average canopy width of $29.0 \pm 1.07 \text{ cm}$. Layer 1 (PPFD $\approx 92 \pm 2.12 \mu\text{mol}/\text{m}^2/\text{s}$ and DLI =3.97 $\text{mol}/\text{m}^2/\text{day}$) had the lowest growth performance, with smaller leaves and shorter plants, and also exhibited some twisted and curled leaves, similar to Layers 2 and 3, with an average canopy width of $23.8 \pm 1.05 \text{ cm}$. The canopy width of lettuce in Layer 3 was 12.8% and 37.4% greater than those in Layers 2 and 1, respectively, while lettuce in Layer 2 had a canopy width 21.9% greater than that of Layer 1.

Table 1 Showing growth measurement of Green Cos Lettuce (Caesar)

Measurement Number	Date	Layer	Number Of Leaves	Leaf Color	Leaf Appearance	Leaf Length (cm)	Leaf Width (cm)	Plant Height (cm)	Canopy Width (cm)
1	15/9/25	1	6	Normal	Normal	3.2	1.4	3.7	3.8
		2	5	Normal	Normal	2.9	1.4	3.5	3.9
		3	5	Normal	Normal	2.9	1.4	3.8	3.8
2	20/9/25	1	7	Normal	Normal	4.8	2.2	5.3	5.7
		2	7	Normal	Normal	4.3	2.3	4.8	5.3
		3	7	Normal	Normal	4.1	2.1	4.5	5.4
3	25/9/25	1	9	Normal	Curled,Wrinkled	8.1	3.7	8	9.4
		2	9	Normal	Curled,Wrinkled	8.3	4	7.9	9.6
		3	9	Normal	Curled,Wrinkled	8.2	4.3	7.8	10.5
4	30/9/68	1	12	Normal	Curled,Wrinkled	13.3	4.6	12.8	15.8
		2	12	Normal	Curled,Wrinkled	12.8	5.3	12.5	16.2
		3	13	Normal	Curled,Wrinkled	13	6	11.8	16.9
5	5/10/25	1	13	Normal	Almost normal	16	6	17.2	19.7
		2	14	Normal	Almost normal	16.3	7.5	17.3	20.3
		3	15	Normal	Almost normal	17.3	8.2	19.6	23.5
6	10/10/25	1	14	Normal	Curled,Wrinkled	19.8	7.1	21.4	22.7
		2	15	Normal	Curled,Wrinkled	23	8.3	19.6	24.3
		3	17	Normal	Curled,Wrinkled	22.2	8.4	23.2	28.1
7	15/10/68	1	17	Normal	Curled,Wrinkled	20.9	7.7	21.8	23.8
		2	19	Normal	Curled,Wrinkled	24.1	8.9	21.7	29
		3	20	Normal	Curled,Wrinkled	23.9	9.1	24.5	32.7

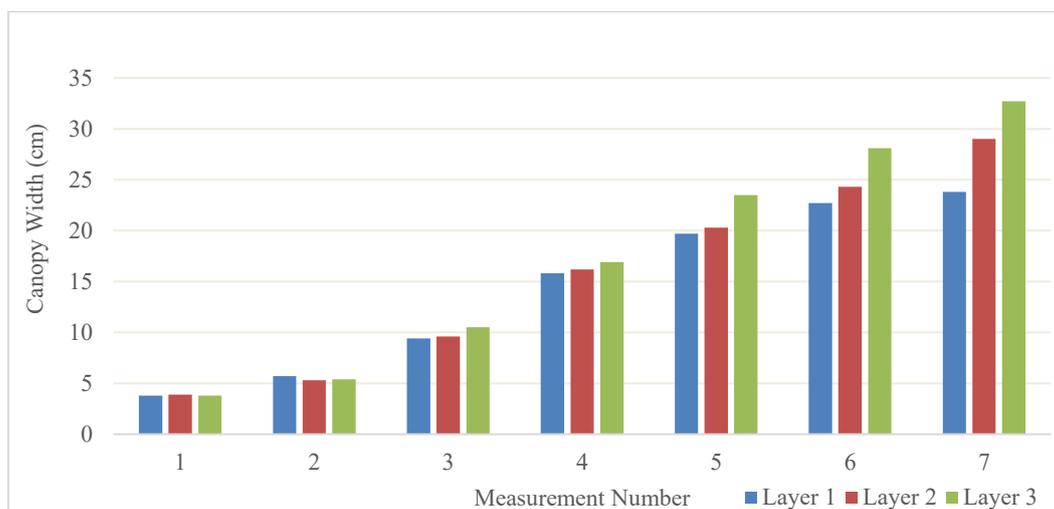


Figure 5 Bar Graph of Plant Canopy Width per Measurement

The percentage improvement in canopy width of lettuce grown on Layer 3 compared with Layers 1 and 2 was calculated using the following expression (Equation 1):

$$\text{Percentage improvement} = \frac{\text{Greater canopy width(cm)} - \text{Smaller canopy width(cm)}}{\text{Smaller canopy width(cm)}} \times 100 \quad (1)$$

Layer 3 (PPFD $\approx 150 \pm 5.48 \mu\text{mol/m}^2/\text{s}$ and average canopy width was $32.7 \pm 1.98 \text{ cm}$.) greater than Layer 2 (PPFD $\approx 122 \pm 2.48 \mu\text{mol/m}^2/\text{s}$ and average canopy width was $29.0 \pm 1.07 \text{ cm}$):

$$\text{Percentage improvement} = \frac{32.7\text{cm} - 29.0\text{cm}}{29.0\text{cm}} \times 100 = 12.8\%$$

Layer 3 (PPFD $\approx 150 \pm 5.48 \mu\text{mol/m}^2/\text{s}$ and average canopy width was $32.7 \pm 1.98 \text{ cm}$.) greater than Layer 1 (PPFD $\approx 92 \pm 2.12 \mu\text{mol/m}^2/\text{s}$ and average canopy width was $23.8 \pm 1.05 \text{ cm}$):

$$\text{Percentage improvement} = \frac{32.7\text{cm} - 23.8\text{cm}}{23.8\text{cm}} \times 100 = 37.4\%$$

Layer 2 (PPFD $\approx 122 \pm 2.48 \mu\text{mol/m}^2/\text{s}$ and average canopy width was $29.0 \pm 1.07 \text{ cm}$.) greater than Layer 1 (PPFD $\approx 92 \pm 2.12 \mu\text{mol/m}^2/\text{s}$ and average canopy width was $23.8 \pm 1.05 \text{ cm}$):

$$\text{Percentage improvement} = \frac{29.0\text{cm} - 23.8\text{cm}}{23.8\text{cm}} \times 100 = 21.9\%$$

To provide a more comprehensive description of light availability, the Daily Light Integral (DLI) was calculated. DLI represents the total number of photosynthetically active photons received per unit area per day and was calculated from PPFD values and photoperiod (Equation 2).

$$\text{DLI} = \frac{\text{PPFD} \left(\frac{\text{mol}}{\mu\text{m}^2\text{s}} \right) \times \text{Photoperiod} \left(\frac{\text{hours}}{\text{day}} \right) \times 3,600}{10^6} \quad (2)$$

Layer 1 had a PPFD of $92 \pm 2.12 \mu\text{mol/m}^2/\text{s}$ and received light for 12 hours per day.

$$\text{DLI} = \frac{92 \mu\frac{\text{mol}}{\text{m}^2\text{s}} \times 12 \frac{\text{hours}}{\text{day}} \times 3,600}{10^6} = 3.97 \text{ mol/m}^2/\text{day}$$

Layer 2 had a PPFD of $122 \pm 2.48 \mu\text{mol/m}^2/\text{s}$ and received light for 12 hours per day.

$$\text{DLI} = \frac{122 \mu\frac{\text{mol}}{\text{m}^2\text{s}} \times 12 \frac{\text{hours}}{\text{day}} \times 3,600}{10^6} = 5.27 \text{ mol/m}^2/\text{day}$$

Layer 3 had a PPFD of $150 \pm 5.48 \mu\text{mol/m}^2/\text{s}$ and received light for 12 hours per day.

$$\text{DLI} = \frac{150 \mu\frac{\text{mol}}{\text{m}^2\text{s}} \times 12 \frac{\text{hours}}{\text{day}} \times 3,600}{10^6} = 6.48 \text{ mol/m}^2/\text{day}$$

These results indicate that light intensity plays a crucial role in promoting growth and uniformity of Green Cos lettuce in hydroponic cultivation. The observed trends are consistent with previous studies reporting that higher Photosynthetic Photon Flux Density (PPFD) enhances leaf expansion, plant height, and overall biomass accumulation. Differences in growth among layers may be attributed to variations in light availability, which affect photosynthesis and energy allocation within the plants. Maintaining other environmental factors, including water and air temperature, relative humidity, photoperiod, pH, and EC constant across layers ensured that the observed differences were primarily due to light intensity. PPFD was measured using a PAR meter (model APm-130, Kunshan Ast Optoelectronics Co., Ltd.) at the canopy level of each layer.

These findings suggest that optimizing light intensity in multi-layer hydroponic systems is essential for producing uniform and high-quality Green Cos lettuce. For practical applications, growers should consider adjusting the number and placement of LED lights to achieve uniform light distribution, thereby enhancing growth performance and marketable yield.

4. Conclusions

The study demonstrated that both light intensity and photoperiod significantly affect the growth performance of Green Cos lettuce (Caesar) in a controlled hydroponic system. Plants grown under the highest light intensity, that is $150 \mu\text{mol/m}^2/\text{s}$ and DLI is $6.48 \text{ mol/m}^2/\text{day}$ (Layer 3), exhibited the best growth, with larger and longer leaves, taller plants, and wider canopies (32.7cm), whereas lower light intensities resulted in reduced growth and less uniformity. All other environmental factors, including water and air temperature, relative humidity, a constant 12-h daily photoperiod, pH, and EC, were maintained uniformly across layers to ensure that the observed differences were primarily due to light conditions. These findings highlight the importance of optimizing light intensity in multi-layer hydroponic systems to achieve uniform and high-quality lettuce production.

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6. References

- [1] Food and Agriculture Organization of the United (FAO). Growing without soil: hydroponics fundamentals, pros and cons [Internet]. 2024 [cited 2025 Nov 05]. Available from: <https://www.fao.org/plant-production-protection/news-and-events/news/news-detail/growing-without-soil--hydroponics-fundamentals--pros-and-cons/en>.
- [2] Resh HM. Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower. 7th ed. CRC Press. 2013.
- [3] Jensen MH, Malter AJ. Protected horticulture: A guide to hydroponic methods. CRC Press. 1995.
- [4] Yang R, Yang H, Ji F, He D. Enhancing the photon yield of hydroponic lettuce through stage-wise optimization of the daily light integral in an LED plant factory. *Agronomy*. 2024;14(12):2949. <https://doi.org/10.3390/agronomy14122949>.
- [5] Pennisi G, Malorgio F, Incrocci L. Effects of light intensity and photoperiod on hydroponic lettuce growth. *Acta Horticulturae*. 2017;1153:155–62. <https://doi.org/10.17660/ActaHortic.2017.1153.20>.
- [6] Li T, Kubota C. Effects of supplemental light quality on growth and phytochemicals of hydroponically grown lettuce. *Environmental and Experimental Botany*. 2009;67(1):59–64. <https://doi.org/10.1016/j.envexpbot.2009.04.007>.
- [7] Boros IF, Székely G, Balázs L, Csambalik L, Sipos L. Effects of LED lighting environments on lettuce (*Lactuca sativa*) in hydroponics. *Scientia Horticulturae*. 2023;318:112766.
- [8] Nitu OA. Optimizing lettuce growth in nutrient film technique: Influence of light intensity. *Agriculture*. 2024;14(9):1896. <https://doi.org/10.3390/agriculture14091896>.
- [9] Su P, Ding S, Li C, Liu Q, Wang Y, Feng Q. Light intensity affects growth, photosynthesis and nutritional properties of *Toona sinensis* sprouts in plant factory. *Photosynthesis Research*. 2026;164(1):3. <https://doi.org/10.1007/s11120-025-01192-z>.
- [10] Hernández-Adasme C, Guevara MJ, Faicán-Benenaula MA, Neira R, Delgadillo D, Muñoz V, Salazar-Parra C, Sun B, Yang X, Escalona VH. Effect of light conditions on growth and antioxidant parameters of two hydroponically grown lettuce cultivars (Green and purple) in a vertical farm system. *Horticulturae*. 2025;11(2):220. <https://doi.org/10.3390/horticulturae11020220>.
- [11] Pinho S, Cammarisano L, Monsees H, Ramírez T, Kloas W, Körner O. (2024). Latitude-dependent implications of lighting regimes on lettuce physiology and resource utilisation in decoupled aquaponics systems. *Environmental and Experimental Botany*. 2024;220:105711. <https://doi.org/10.1016/j.envexpbot.2024.105711>.