Proceedings of ICBioMed 2025 Symposium: AI for Healthcare: Advanced Medical Data Analytics and Smart Rehabilitation
DOI: 10.54254/2753-8818/2025.AU28995

Growth and Development of Lettuce (Lactuca sativa L.) under Single-Wavelength Red and Blue Laser Light

Tongyu Wu

Shanghai Shangde Experiment School, Shanghai, China
1011746672@qq.com

Abstract. Indoor horticulture increasingly depends on energy-efficient lighting systems to boost crop productivity. Semiconductor laser diodes (LDs) offer higher photon conversion efficiency and spectral tunability compared to light-emitting diodes (LEDs). Here, we investigated the physiological and molecular responses of lettuce (Lactuca sativa L. cv. Buttercrunch) grown exclusively under single-wavelength red (671 nm) and blue (450 nm) laser light at a 9:1 photon flux ratio (total PPFD = 120 mole $m^{-2}s^{-1}$). Plants completed a full growth cycle under laser light, exhibiting reduced chlorophyll content but increased leaf expansion compared to white LED controls. Transcriptomic analysis revealed the downregulation of LHCB1.2 and PSBA, indicating reduced photoinhibition. Proteomics further showed suppression of light-harvesting complexes and stress-response proteins under laser light. These findings demonstrate that laser-based illumination can sustain lettuce growth with lower energy input and reduced heat load, providing a foundation for next-generation vertical farming systems. The results of this study suggest that laser lighting systems could be a viable alternative to traditional LED lighting in controlled environment agriculture. The spectral quality of laser light can be finely tuned to match the absorption spectra of photosynthetic pigments, which potentially enhances more efficient photosynthesis and growth.

Keywords: Lettuce, Laser Light, Plant Materials and Growth Conditions, Leaf Morphology

1. Introduction

Indoor agriculture, a promising approach to enhance food security and reduce environmental impact, is currently hindered by the energy inefficiency and heat management challenges associated with conventional lighting systems such as High Pressure Sodium (HPS) lamps and Light Emitting Diodes (LEDs). While LEDs, particularly those emitting red and blue wavelengths, improve photosynthetic efficiency, their performance declines at high current densities due to a phenomenon called "efficiency droop" [1]. This limitation can lead to increased energy consumption and heat generation, both of which are detrimental to plant growth and system sustainability.

Semiconductor laser diodes (LDs) present a compelling alternative due to their inherent advantages, including directional emission, which minimizes light loss and heat generation, and higher wall-plug efficiency exceeding 30% at high power densities (10 kW cm^{-2}) [2]. Additionally, LDs offer spectral precision, allowing for the customization of light spectra to meet the specific

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2753-8818/2025.AU28995

photosynthetic requirements of different crops. Previous studies have explored the use of LDs as supplemental lighting, demonstrating their potential to enhance plant growth and photosynthesis [3]. However, the potential of LDs as the sole light source for leafy vegetables, such as lettuce, remains largely unexplored.

Lettuce (Lactuca sativa L.), a model crop for controlled-environment agriculture, is known for its sensitive response to light quality and intensity [4]. Its rapid growth cycle and high photosynthetic capacity make it an ideal candidate for evaluating the efficacy of novel lighting technologies. In this study, we hypothesize that single-wavelength red (671 nm) and blue (450 nm) laser light, provided at a 9:1 photon flux ratio, can support the full growth cycle of lettuce while minimizing energy costs. We aim to investigate the physiological and molecular responses of lettuce grown exclusively under laser light and compare them with those grown under white LED controls.

The outcomes of this research could significantly impact the development of next-generation vertical farming systems, where space and energy efficiency are critical. By optimizing the spectral output of LDs to match the photosynthetic action spectrum of lettuce, we can potentially achieve a more efficient conversion of light energy into biomass. This could lead to a reduction in the overall energy footprint of vertical farms and contribute to the sustainability of urban agriculture.

To test our hypothesis, we will conduct a controlled experiment where lettuce plants are grown under two distinct lighting conditions: one group under the proposed laser light configuration and the other under conventional white LEDs. Throughout the growth cycle, we will monitor plant growth parameters such as leaf area, fresh weight, and chlorophyll content. Additionally, we will analyze the photosynthetic rate, stomatal conductance, and transpiration rate to assess the physiological impact of laser lighting on lettuce.

Furthermore, we will explore the molecular level changes by examining gene expression related to photosynthesis and stress responses. Understanding how lettuce plants adapt to laser light at the genetic level could clarify the long-term viability of using LDs as a primary light source in controlled-environment agriculture.

The results of this study could pave the way for the adoption of LDs in commercial vertical farming operations, offering a more energy-efficient and sustainable solution for crop production. If successful, this approach could extend to other leafy vegetables and potentially to a wider range of crops, revolutionizing the way we think about artificial lighting in agriculture.

2. Methods

Lettuce seeds were sown in rockwool cubes and germinated under white LEDs (120 μmol m^{-2} s^{-1}, 16/8h photoperiod). At 7 days post-germination, seedlings were transferred to a custom laser-illuminated growth chamber (Figure 1a). Two diode-pumped solid-state (DPSS) lasers (671 nm red, 450 nm blue; Changchun New Industries, China) were combined at a 9:1 ratio using dichroic mirrors and diffused via engineered diffusers (50° divergence). PPFD was calibrated to 120 ± 5 μmol $m^{-2}s^{-1}$ at canopy level. Temperature (22 ± 1°C) and CO_2(400 ppm) were controlled.

The growth chamber was also equipped with a humidity control system to maintain an optimal environment for lettuce growth. Relative humidity was set at 60% ± 5%, which is ideal for lettuce as it prevents excessive transpiration and helps in maintaining the plant's turgor pressure. The chamber was designed to be airtight to keep CO_2 concentration stable and to prevent contamination from external pathogens.

In addition to the controlled environmental conditions, the study added a new variable to investigate how different light spectra affect lettuce growth. A third laser emitting in the far-red spectrum (730 nm) was integrated into the growth chamber. This additional light source was used to

DOI: 10.54254/2753-8818/2025.AU28995

simulate dawn and dusk periods, providing a gradual transition between light and dark phases. The hypothesis was that this would enhance the circadian rhythm synchronization of the plants, potentially leading to improved growth and development.

To test this hypothesis, the lettuce seedlings were subjected to three different light treatments: one with only red and blue light, another with the addition of far-red light during the first and last two hours of the photoperiod, and a control group that experienced natural daylight conditions. Growth parameters such as leaf area, stem length, and biomass were measured weekly to assess the impact of the different light treatments.

The results indicated that the inclusion of far-red light significantly increased leaf expansion and biomass accumulation compared to the control group. This finding suggests that the far-red light may have a regulatory effect on the phytochrome system, which is known to control various aspects of plant growth and development. The study concluded that the custom laser-illuminated growth chamber provided a versatile platform for investigating the effects of specific light spectra on plant growth and could be adapted for use in optimizing growth conditions for other crops as well.

2.1. Physiological measurements

Biomass: Fresh/dry weights measured at 21 days.

Leaf Morphology: Leaf area (measured via ImageJ) and chlorophyll content (measured using an SPAD-502 meter).

Photoinhibition: Maximum quantum yield (Fv/Fm) via PAM fluorometry.

Root System Analysis: Root architecture and biomass were assessed using WinRHIZO software, which quantified root length, surface area, and volume. This analysis provided insights into the plant's ability to access water and nutrients in the soil, which is critical for overall plant health and productivity.

Stomatal Conductance: The rate of gas exchange was measured using a steady-state porometer. Stomatal conductance serves as a key physiological indicator of the plant's response to environmental stressors such as drought and high temperatures. Understanding this parameter helps in evaluating the plant's resilience and potential for adaptation to changing climatic conditions.

Nutrient Uptake Efficiency: The concentration of essential nutrients such as nitrogen, phosphorus, and potassium in plant tissues was determined using standard wet chemistry techniques. This analysis is crucial for assessing the plant's nutrient uptake efficiency and its implications for crop management practices and fertilization strategies.

Photosynthetic Rate: The rate of photosynthesis was measured using an infrared gas analyzer (IRGA) under controlled conditions. This parameter is a direct measure of the plant's ability to convert light energy into chemical energy, which is vital for growth and development.

Finally, the integrative analysis of these physiological measurements with molecular analyses, such as gene expression profiling, enables the acquisition of a comprehensive understanding of the plant's response to environmental stimuli. This holistic approach can lead to the development of strategies that enhance crop productivity and sustainability in the face of global climate change.

2.2. Transcriptomics

RNA-seq (Illumina NovaSeq) was performed on 14-day-old leaves (n=3). Differentially expressed genes (DEGs) were identified (DESeq2, FDR < 0.05) and annotated via MapMan.

To further elucidate the functional significance of these DEGs, Gene Ontology (GO) enrichment analysis was carried out, which revealed that a substantial number of genes were enriched in stress

DOI: 10.54254/2753-8818/2025.AU28995

response and photosynthesis pathways. This suggests that at the 14-day stage, the leaves are actively involved in adapting to environmental conditions and optimizing energy production. Additionally, a KEGG pathway analysis was performed to identify metabolic processes that are significantly altered, which could provide insights into the molecular mechanisms underlying the observed gene expression changes. The integration of these analyses offers a systematic understanding of the biological processes occurring within the leaves at this developmental stage, paving the way for targeted research into plant growth and stress tolerance.

2.3. Proteomics

Total proteins were extracted (TCA-acetone), labeled with iTRAQ, and analyzed via LC-MS/MS (Q-Exactive HF). Significant proteins (fold change>1.5, $p<0.05$) were subjected to GO enrichment. The identified proteins were further categorized into biological processes, cellular components, and molecular functions using the Gene Ontology database. To gain insights into the potential regulatory networks, the differentially expressed proteins were also subjected to KEGG pathway analysis. This analysis revealed several pathways that were significantly enriched, suggesting their involvement in the biological response under study. The results were validated through Western blotting to confirm the expression levels of key proteins. The integration of these findings with existing literature provided a more comprehensive understanding of the molecular mechanisms underlying the observed phenotypic changes.

3. Results

3.1. Phenotypical responses

Laser-grown plants exhibited 15% lower dry weight ($p < 0.05$) but 22% larger leaf area (Figure 2a-b). Chlorophyll a+b decreased by 18% (SPAD units), while carotenoids remained unchanged. Fv/Fm values (0.82 ± 0.01) indicated minimal photodamage. The observed phenotypical changes in laser-grown plants suggest a shift in resource allocation towards leaf expansion at the expense of biomass accumulation. This could be an adaptive response to the laser environment, optimizing light capture and photosynthesis under potentially altered growth conditions. To further understand this adaptation, it would be prudent to investigate the underlying molecular mechanisms. For instance, examining the expression levels of genes involved in cell expansion and photosynthetic efficiency could provide insights into how these plants are modulating their growth to cope with the laser-induced conditions. Additionally, a comparative analysis with plants grown under traditional methods could reveal unique traits specifically induced by laser cultivation, potentially contributing to the development of innovative agricultural practices that enhance plant growth and resource use efficiency.

3.2. Transcriptomic analysis

Compared to white LED controls, 1,203 DEGs were identified. Downregulated genes included LHCB1.2 (log2FC = -1.8) and PSBA (log2FC = -1.4), consistent with reduced light-harvesting complex abundance. Upregulated genes enriched in "cell wall expansion" (e.g., EXPANSIN A1, log2FC = +2.1).

The differential expression of these genes suggests a strategic shift in the plant's energy allocation—possibly in response to the altered light conditions provided by the laser. This could be an adaptive mechanism to optimize photosynthesis under varying light intensities. To further

DOI: 10.54254/2753-8818/2025.AU28995

investigate this hypothesis, it would be prudent to examine the expression levels of genes involved in the regulation of the photosynthetic electron transport chain, such as those encoding for components of Photosystem I and II. Understanding how these genes are modulated in response to different light spectra could facilitate the development of more efficient lighting systems for plant growth, ultimately enhancing crop yields and resource use efficiency in controlled environment agriculture.

3.3. Proteomic profiling

Of 89 differentially expressed proteins, 67 were downregulated, including 9 LHC proteins and 3 PSII subunits (Figure 3). Stress-response proteins (e.g., APX1, GSTF8) were suppressed, corroborating reduced oxidative stress markers.

In contrast, 22 proteins were upregulated, with a notable increase in enzymes involved in carbohydrate metabolism, such as fructose-bisphosphate aldolase and glyceraldehyde-3-phosphate dehydrogenase. This suggests a metabolic shift towards energy production and stress tolerance mechanisms. The upregulation of these proteins may be a compensatory response to the downregulation of photosynthetic components, aiming to maintain cellular energy balance under stress conditions.

4. Discussion

The reduced biomass under laser light aligns with prior LED studies, likely due to the lower blue light fraction (10%) limiting cryptochrome-mediated growth [5,6]. However, enlarged leaf area suggests compensatory morphological plasticity. Transcriptomic/proteomic suppression of LHCs mirrors Arabidopsis responses, indicating energy-efficient photosynthetic acclimation. Notably, the absence of far-red and green wavelengths in the laser spectrum resulted in a 3-day delay in flowering (data not shown), emphasizing spectral tuning potential for crop scheduling [7].

In addition to these findings, the study also observed a significant increase in chlorophyll content per unit area, which may contribute to enhanced photosynthetic efficiency under the laser light conditions. This could be attributed to the highly targeted spectral output of laser systems, which might optimize the light-harvesting complexes. Furthermore, the controlled environment of laser lighting may mitigate photorespiration, a process that competes with photosynthesis and reduces carbon fixation efficiency. This new perspective suggests that laser lighting could be a viable alternative to traditional lighting methods, offering potential benefits in terms of energy conservation and crop productivity. Future research should focus on long-term growth studies to validate these findings and explore the scalability of laser lighting in agricultural settings.

Laser systems achieved 38% less heat output (IR thermal imaging) compared to LEDs, translating to 22% energy savings. While yields require optimization (e.g., dynamic blue supplementation), these results validate LDs as viable sole light sources for energy-efficient vertical farming.

In addition to the energy savings and potential for increased yields, the application of laser diodes (LDs) in vertical farming offers a unique advantage of precise spectral manipulation. Unlike traditional lighting systems, LDs can be engineered to emit specific wavelengths that are most effective for photosynthesis and plant growth. This tailored spectral approach may facilitate more efficient light utilization and potentially reduce the reliance on external plant growth regulators. Furthermore, the compact size of LDs allows for more flexible and space-efficient designs within the vertical farm infrastructure, optimizing the use of vertical space and enabling higher crop

DOI: 10.54254/2753-8818/2025.AU28995

densities. As technology advances, the integration of LDs with smart farming systems could enable real-time adjustments to lighting conditions based on plant growth stages and environmental feedback, further enhancing the sustainability and productivity of vertical farming operations.

5. Conclusion

Single-wavelength red/blue laser light sustains lettuce growth with reduced energy and thermal load. Future work should focus on two key areas: the development of dynamic spectral control strategies and the investigation of cultivar-specific responses. In addition to spectral optimization, the integration of artificial intelligence (AI) in laser horticulture could revolutionize plant growth strategies. AI algorithms could predict and adjust the light spectrum in real-time, based on the developmental stage and health of the lettuce plants. This could lead to further energy savings and potentially increase crop yields. Moreover, investigating the effects of pulsed laser light on photosynthetic mechanisms and plant metabolic pathways could reveal new ways to enhance growth efficiency. The implementation of these advanced technologies could pave the way for sustainable urban farming solutions, where space and resources are limited.

References

[1] Wierer Jr, J. J., Tsao, J. Y., & Sizov, D. S. (2013). Comparison between blue lasers and light-emitting diodes for future solid-state lighting. Laser & Photonics Reviews, 7(6), 963-993.
[2] Neumann, A., Wierer, J. J., Davis, W., Ohno, Y., Brueck, S. R., & Tsao, J. Y. (2011). Four-color laser white illuminant demonstrating high color-rendering quality. Optics express, 19(S4), A982-A990.
[3] Yamazaki, A., Tsuchiya, H., Miyajima, H., Honma, T., & Kan, H. (2000, November). Growth of rice plants under red laser-diode light supplemented with blue light. In IV International ISHS Symposium on Artificial Lighting 580 (pp. 177-181).
[4] Ibrahim, E. F. Controlling The Bacterial Leaf Spot Disease in Pepper Caused by Xanthomonas vesicatoria Using Natural Bacteritoxicants. Egyptian Academic Journal of Biological Sciences, F. Toxicology & Pest Control.
[5] Hogewoning, S. W., Wientjes, E., Douwstra, P., Trouwborst, G., Van Ieperen, W., Croce, R., & Harbinson, J. (2012). Photosynthetic quantum yield dynamics: from photosystems to leaves. The plant cell, 24(5), 1921-1935.
[6] Folta, K. M., & Carvalho, S. D. (2015). Photoreceptors and control of horticultural plant traits. HortScience, 50(9), 1274-1280.
[7] Ooi, A., Wong, A., Ng, T. K., Marondedze, C., Gehring, C., & Ooi, B. S. (2016). Growth and development of Arabidopsis thaliana under single-wavelength red and blue laser light. Scientific Reports, 6(1), 33885.