Received: 5 August 2024 | Revised: 22 September 2024 | Accepted: 24 October 2024 | Published online: 30 October 2024

RESEARCH ARTICLE

Journal of Optics and Photonics Research
2024, Vol. 00(00) 1–9
DOI: 10.47852/bonviewJOPR42024031

BON VIEW PUBLISHING

The Impact of Varying Ratios of Light Quality Emitted by Light-Emitting Diodes on the Butter Lettuce

Jun Zou[1], Wenbin Liu[1], Dawei Wang[1], Shipeng Luo[1], Yan Shen[2], Mingming Shi[1,*] and Hongliu Xu[3]

[1]*School of Science, Shanghai Institute of Technology, China*

[2]*Shanghai Yingzhi Technology Co., Ltd, China*

[3]*Shanghai Agricultural Beauty Technology Development Co., Ltd., China*

Abstract: Light-emitting diodes (LEDs) are considered the optimal artificial light source for plant factories, yet further research is needed to understand the impact of LED light quality on plant growth. This experiment investigated the growth and development of butter lettuce under varying ratios of red and blue light provided by LEDs. The specific effects of different red and blue light quality ratios on butter lettuce growth were systematically tracked and recorded, with comprehensive measurements of growth parameters and photosynthetic characteristics. Empirical findings revealed that a higher red light component compared to blue light led to improved butter lettuce characteristics. These included increased leaf length and width, elevated plant height, higher relative chlorophyll content, and an increased net photosynthetic rate. The study also highlighted that the light quality requirements of lettuce fluctuate across different growth stages, allowing for adaptable modulation of lighting conditions to align with specific growth stage needs. Total fresh weight, total dry weight, and dry matter content of lettuce reached the highest values in the R8B2 treatment with 80% red light and 20% blue light, and the percentage differences reached 29.2%, 23.1%, and 13.9%, respectively. Additionally, the photosynthetic chlorophyll content and net photosynthetic rate exhibited maximum percentage differences of 22.22% and 14.6%, respectively. In conclusion, the experimental evidence supports that an R8B2 spectral composition (80% red and 20% blue light) in a controlled indoor setting represents the optimal light environment for the accelerated growth and superior quality of butter lettuce.

Keywords: LED, net photosynthetic rate, butter lettuce, light quality, relative chlorophyll content

1. Introduction

The manipulation of spectral light components has proven effective in optimizing plant growth [1]. Currently, this technique is widely used in horticulture to enhance the yield and quality of various crops. It achieves this by inducing significant changes in both primary and secondary plant metabolism [2, 3]. Light-emitting diode (LED) technology offers a superior alternative to traditional lighting methods, boasting advantages such as high luminous efficacy, minimal energy consumption, low cost, and reduced heat generation [4]. It is believed that blue light (400–500 nm) and red light (600–700 nm) are particularly effective in the process of photosynthesis compared to other wavelengths of light [5]. During photosynthesis, plants primarily utilize red and blue light, each playing an indispensable role in the process [6, 7]. LED technology optimizes the balance between these essential wavelengths, resulting in significant improvements in plant growth and development.

Many studies have emphasized the role of blue light in regulating plant growth and morphology as well as the significant impact of red light in plant growth and development. For example, research has shown that the proportion of blue light in the spectrum significantly affects the biological characteristics of dill plants. Interestingly, a low dose of blue light (20%) positively impacts the plant's leaf area [8]. A combination of red and blue light thickens tomato leaves and enhances photosynthesis compared to monochromatic red light [9]. Studies have shown that blue light can lead to compact headscarf plants and earlier flowering [9]. In addition, red light has a wide range of important effects on the growth and physiological processes of plants [10]. Research has demonstrated that Brassica napus exhibits the highest abscising acid content under red light conditions [11]. A study conducted by Yasuhito Sakuraba and colleagues revealed that red light signaling enhances phosphorus uptake in rice by regulating the expression of relevant genes [12]. Furthermore, a pioneering study led by Pavlos Kalaitzoglou and his team concluded that tomato plants grown under artificial light lacking far-red wavelengths exhibit a series of shade-avoidance responses [12]. Specifically, red light accelerates the growth of tomato stems and petioles, resulting in elongated and loosely structured plants [13].

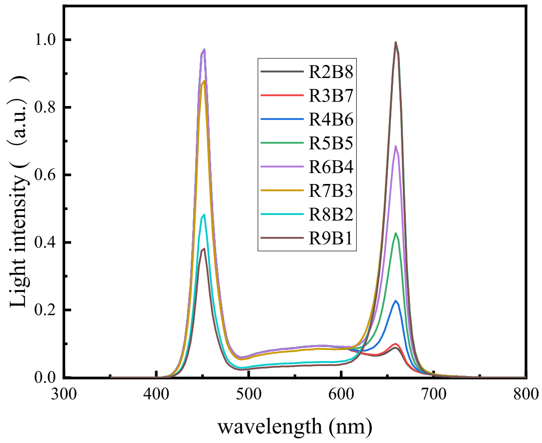
Based on the significant effects of red and blue light on plant growth [14], indoor controlled environment plant factories, growth chambers, or plant production units using free-space optical

*Corresponding author: Mingming Shi, School of Science, Shanghai Institute of Technology, China. Email: mingmingshi@sit.edu.cn

communication [15–17] of artificial light are becoming increasingly popular in commercial leafy vegetable cultivation and research in the field of plant science [17, 18]. Lettuce (*Lactuca sativa L.*) is widely grown in plant factories because of its low cost and high density of cultivation, ease of management, and short harvest cycle. It is a model crop for many researchers to study plant responses to different light environments [19].

Lettuce, as one of the most common crops, has garnered considerable attention with respect to the influence of light quality on its growth and development. Given the multitude of factors affecting lettuce's growth and development, scholars have presented various perspectives on the effects of different light qualities. Joo Hwan Lee and colleagues found that BR-LED produced favorable results, including increased crop fresh weight, increased leaf thickness, and increased content of substances such as ascorbic acid, resulting in the highest overall preference. Therefore, BR-LED is considered to be the best choice for cultivating lettuce in an artificial environment [20]. Lyubov Yudina and associates concluded that the efficiency of lettuce cultivation can be improved by utilizing light sources with narrow spectral bands [18]. Akvilė Viršilė's research suggested that lettuce responses to dynamic light strategies are influenced by the specific lettuce variety being grown [21]. The findings of Noriko Ohtake and their team indicated that plants cultivated under alternating red/blue light exhibited higher net assimilation rates and greater total and projected leaf area (an indicator of the proportion of leaf area that absorbs more light) compared to other lighting conditions [6]. However, Bo-Sen Wu and colleagues demonstrated that amber light outperformed red light in promoting photosynthetic activity and plant productivity [22]. The aforementioned results hold practical relevance in current agricultural production. This experiment specifically focuses on examining the impact of LED light with varying red-to-blue ratios on the growth and development of butter lettuce within real-world applications. This experiment is the first of its kind to present the different growth conditions of cream lettuce under multiple gradients of red and blue light mass ratios in a fully enclosed artificial light plant factory, controlling for other environmental factors that may have an impact on plant growth conditions during the plant growth process to ensure that reliable experimental results are obtained. Unlike other traditional ways of categorizing light, the purpose of the experiment was to pinpoint the optimal light quality ratio for the growth of cream lettuce and to point out the shortcomings of other light quality ratios of different gradients in comparison with it, thus providing a valuable and important reference for growing lettuce in plant factories. Key parameters such as cream lettuce leaf size (length and width), plant height, relative chlorophyll content, and net photosynthetic rate were also meticulously evaluated to ensure that the experimental results could effectively guide production. The primary goal was to pinpoint the optimal light quality ratio for promoting the growth of butter lettuce and, in turn, establish a standardized light guideline to enhance practical production methods.

Figure 1
Spectrograms with different light mass ratios



2. Methods

2.1. Plant materials and growth conditions

Experimental materials: The experimental material was 200 butter lettuce seeds.

Planting conditions: The seeds were planted on a substrate block by hand sowing, placed in a greenhouse with 80% humidity and 25 degrees Celsius for germination, and after seven days, transplanted into LED supplemental light seedbeds, which were irradiated and supplemented with an LED light source, and cultivated hydroponically throughout the growing period of the plant.

Treatment group setting: Eight control groups were included in the experiment, R2B8 (red/blue—2:8), R3B7, R4B6, R5B5, R6B4, R7B3, R8B2, R9B1 (wavelengths as shown in Figure 1), where the ratio set for the actual production of the electrical power of the lamp holder. To ensure the accuracy of our experimental results, we adjusted the LED light intensity to account for variations in the photosynthetic photon flux density (PPFD) of different light qualities, maintaining a PPFD of over 200 μmol·m^{-2}·s^{-1} for each type of light.

Planting position: Lettuce seedlings were placed on specialized plant filler racks, as shown in Figure 2. Four hole trays were placed in each layer of the seedbed before planting, and each tray was planted with 50 lettuce seedlings. After planting, two foam plates were placed in each layer, each with 21 lettuce plants. The ambient temperature (23°C), humidity (80%), and daily light hours (16 h) were kept consistent for each layer.

Parameters recorded: Each layer of measured data position lettuce was labeled as 1,2,3,4, and the plant replenishment lamp holder was numbered as A, B, C, D, E, F, G, H according to the order of the red and blue light quality ratio (from R2B8 to R9B1), and then the growth data of the labeled plants were measured once every 2 days starting on the 8th day after the planting of lettuce, and then once every 2 days after the planting of lettuce (on the 18th day after the planting), and once every 2 days on the 20th, 25th, 28th, 32nd, and 37th days after the planting of lettuce. After planting (18th day after planting), the growth data of the labeled plants were measured on the 20th, 25th, 28th, 32nd, and 37th days, respectively. Four lettuce plants were measured for each light quality ratio, and the data measured for each lettuce plant were repeated three times, and the average value was taken as the reference data. At the final harvest, we measured net the photosynthetic rate, chlorophyll index, intercellular CO2 concentration, and stomatal conductance using the same methods. Each parameter was measured three times, and the average value was taken as the final measurement.

2.2. Light environment design

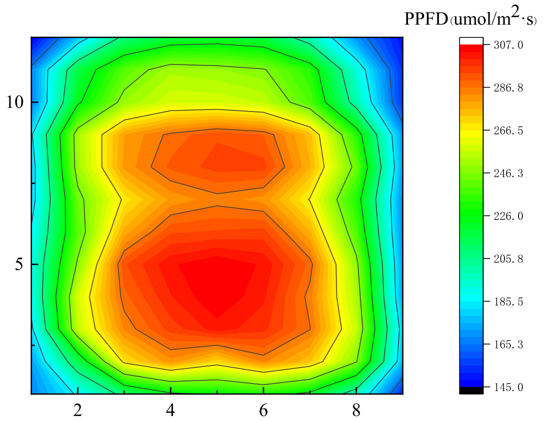
2.2.1. Light source design

The light source design is a crucial element of supplemental equipment to cater to the specific demands of practical agricultural production. Current research primarily emphasizes the utilization of red and blue light [23, 24]. Red light plays a pivotal

Figure 2
A picture of lettuces growing under LED lamps

role in enhancing plant growth by promoting root morphogenesis, stem elongation, and leaf growth. Additionally, it regulates plant metabolism, leading to increased accumulation of photosynthetic products. On the other hand, blue light contributes to sturdier and more compact plant structures, elevates chlorophyll content, and stimulates nitrogen metabolism [24]. In order to determine the optimal red and blue light ratio for lettuce growth [25], in this experiment, a high spatial light uniformity plant supplemental light stand was used to supplement light for cream lettuce in a fully enclosed artificial light plant factory, and the supplemental light stand used was able to control the light quality, light intensity, and light environment so that the plant could be stably located in the optimal external growth environment, which solved the constraints of the unsuitable light environment on the plant's production activities. This research aims to shed light on the ideal balance between red and blue light wavelengths to maximize the growth potential of lettuce plants.

Figure 3
Light intensity distribution in lettuce planting plane



2.2.2. Optical uniformity design

To mitigate the impact of uneven lighting on experimental accuracy and ensure uniform light supplementation, each layer of the seedbed was equipped with 12 LED light bars. We conducted measurements of the PPFD of these light sources at the surface of the seedbeds, and the distribution of planting plane light uniformity is shown in Figure 3. To guarantee uniformity, PPFD readings were taken at 15 evenly selected points on the seedbed, positioned 30 cm away from the supplemental light source. This meticulous approach aimed to maintain consistency in the light distribution, thus enhancing the precision and reliability of the experimental outcomes.

2.3. Methods of measurement

Measurement of growth: Lettuce plant height, leaf length, and leaf width were measured with a straightedge.

Measurement of dry and fresh weight: For fresh weight, lettuce was picked to remove decayed and dried portions of the leaves and then immediately measured using an accurate electronic scale. For dry weight, lettuce was placed in a drying oven for 24 hours and then weighed using an accurate electronic scale [26].

Measurement of photosynthetic characteristics: photosynthesis meter (LICOR LI-6400). Net photosynthetic rate, stomatal conductance, intercellular carbon dioxide concentration, and transpiration rate were measured. SPAD assays were performed using a chlorophyll analyzer on the largest leaves of lettuce in an environment with a temperature of 23°C and a humidity of 80%.

Statistical Analysis: The experiment utilized a fixed block design with 32 samples per group to determine the growth parameters of lettuce. Statistical analyses were performed using IBM SPSS Statistics 27 (Amonk, New York, NY, USA). The experimental results were analyzed through analysis of variance and Tukey's test.

3. Result and Discussion

3.1. Lettuce growth and morphology

The changes in the plant height of lettuce plants under various light quality ratios are illustrated in Figure 4. The figure reveals that during the initial stages of lettuce growth, an excessively high proportion of blue light inhibited plant height. Specifically, on days 8 and 12, when the proportion of blue light exceeded that of red light, the plant height of lettuce plants was notably lower compared to the experimental group with a higher proportion of red light. By the 20th day, lettuce plants were divided, and the leaves were in the recovery phase from wilting, resulting in decreased measured plant heights. Subsequent measurements on the 28th and 32nd days indicated that the effects of different light quality ratios on plant heights were not significant after the division of lettuce plants.

As depicted in Figure 5, during the initial phase of plant growth, the length and width of plant leaves exhibited insensitivity to variations in light quality ratios. There were minimal differences observed on the 8th, 12th, 16th, and 20th days of growth. However, after the splitting of lettuce, indicating the later stage of lettuce growth, different light quality ratios significantly influenced leaf growth. Notably, on the 37th day, the experimental group with a higher proportion of red light than blue light displayed greater length and width of plant leaves compared to the group with a higher proportion of blue light. Remarkably, the plant leaf length and width reached their peak when the photomass ratio was R8B2, aligning with the findings of Rūta Sutulienė et al. [27]. The reduction in red and blue photomass ratios could have triggered the response of leaf area to highlight intensities, consequently reducing leaf length and width [28]. This outcome is associated with blue light's ability to limit cell extension and differentiation [29]. Leaf extension is regulated by different genes in vertical and horizontal directions, and blue light induces an imbalance in the expression of these genes, leading to the suppression of leaf extension [30]. Moreover, red light alone can decelerate leaf growth [31], emphasizing the essential need for an appropriate proportion of blue light. Previous studies have indicated that the combination of red and blue light has the most positive impact on the growth, development, and physiological processes of leafy vegetables such as lettuce [32]. This highlights the fact that monochromatic blue or red light alone cannot adequately support normal plant growth [33].

The data analysis presented in Table 1 clearly indicates significant differences ($p < 0.05$) in the relative chlorophyll content, net weight, dry weight, and dry matter content of lettuce plants under different light quality ratios. Chlorophylls are pivotal pigments for photosynthesis, absorbing light energy and converting it into chemical energy to drive plant growth and development [34]. Consequently, assessing the relative chlorophyll content is crucial for evaluating plant photosynthetic efficiency and overall growth. The net and dry weight of lettuce are indicative of the plant's water content, a vital parameter for studying its drought tolerance and disease resistance [35]. Additionally, the net dry weight of lettuce serves as a significant indicator to reflect the plant's growth rate and growth cycle,

Figure 4
Schematic diagram of lettuce plant height growth under different light quality ratios

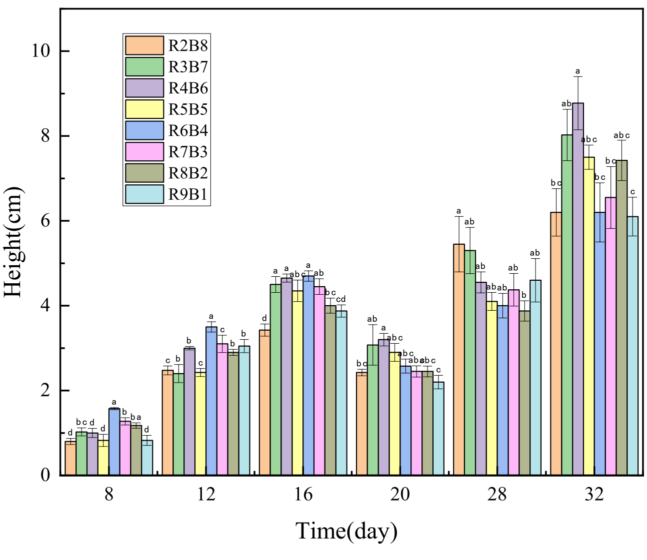


Figure 5
Schematic diagram of lettuce leaf length and width growth under different light quality ratios

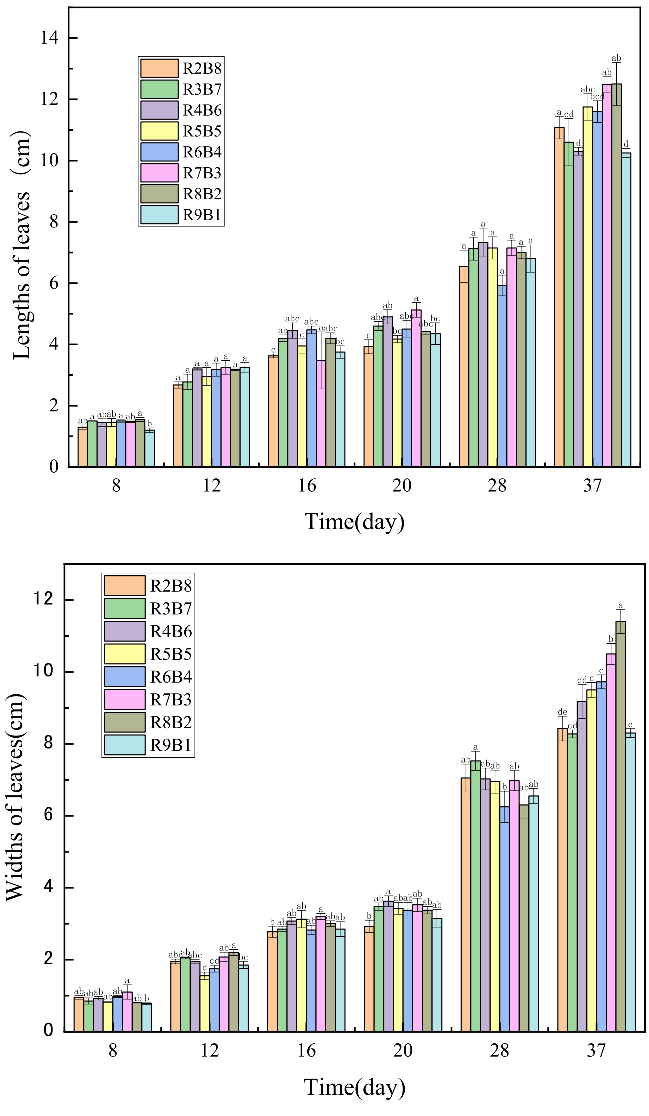


Table 1
Values of relative chlorophyll content, net weight, dry weight, and dry matter content of lettuce plants with different light quality ratios, values are presented as mean ± standard error. Means with the same letter in each column are not significantly different at $p < 0.05$

Light quality	SPAD	Net weight (g)	Dry weight (g)	Dry matter content
R2B8	30.35 ± 1.95d	45.00 ± 2.94b	1.95 ± 0.03d	4.35 ± 0.29b
R3B7	35.92 ± 1.30c	44.00 ± 2.83bc	1.87 ± 0.04e	4.27 ± 0.33b
R4B6	34.5 ± 3.35c	45.50 ± 3.70b	1.90 ± 0.03e	4.19 ± 0.30bc
R5B5	40.52 ± 2.81a	55.00 ± 2.58a	2.13 ± 0.02bc	3.88 ± 0.16c
R6B4	41.32 ± 1.51a	34.00 ± 4.24d	1.31 ± 0.03f	3.89 ± 0.39c
R7B3	39.62 ± 1.31ab	44.00 ± 1.83bc	2.09 ± 0.05d	4.76 ± 0.25a
R8B2	39.02 ± 2.27bc	56.25 ± 1.26a	2.54 ± 0.04a	4.51 ± 0.09ab
R9B1	39.97 ± 2.26ab	40.75 ± 1.71c	1.95 ± 0.04b	4.77 ± 0.23a

providing valuable insights into its growth patterns and rhythms. The experimental results indicate that red light has a more positive impact on the dry matter content, dry weight, fresh weight, and SPAD of lettuce. Specifically, increasing the red light ratio has a more significant effect on dry matter content, dry weight, and fresh weight compared to SPAD. The R8B2 light ratio combination resulted in the highest values for dry matter content, dry weight, and fresh weight of lettuce. Under this light ratio, the dry matter content, dry weight, and fresh weight of lettuce reached their maximum values, showing a maximum difference of 29.2%, 23.1%, and 13.9%, respectively. This observation aligns with the findings of Lyubov Yudina [36], who demonstrated that the increase in red light intensity was associated with decreased dark respiration, leading to an increase in lettuce weight. These results also corroborate with studies by Son and Ahmed [37], which highlighted that red light with wavelengths between 600 and 700 nm is the most effective range for promoting growth rate and photosynthesis in lettuce.

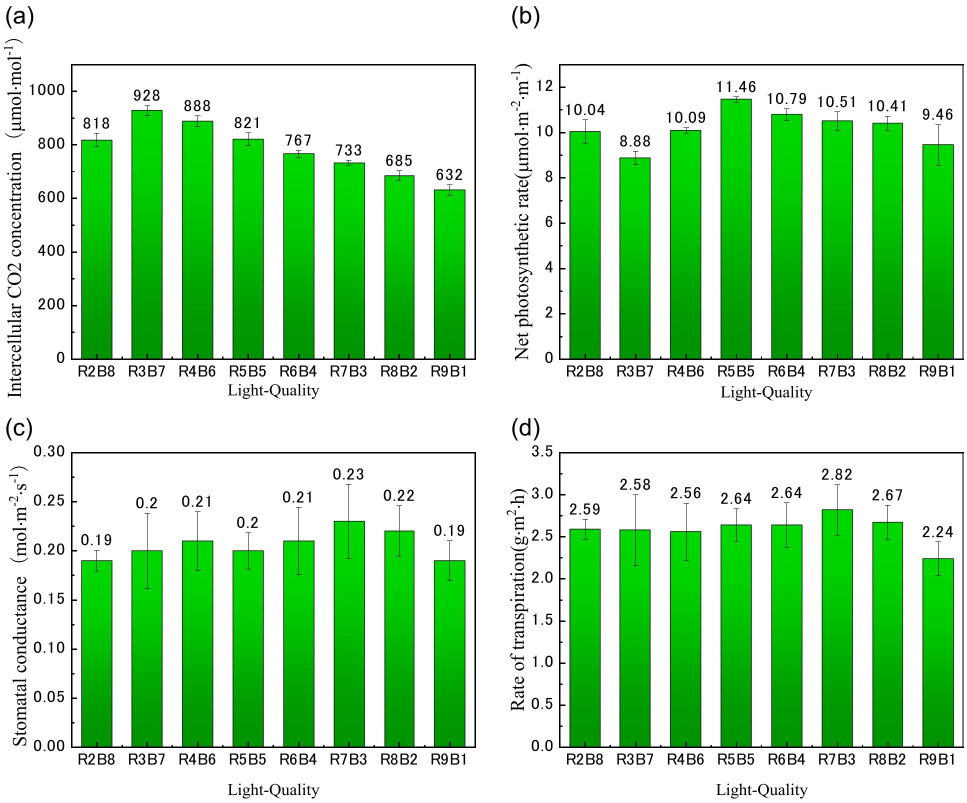
3.2. Physiological activities of lettuce

Intercellular carbon dioxide concentration stands as a critical physiological indicator for plant growth, and maintaining an appropriate level is essential for the healthy development of lettuce plants. If the intercellular carbon dioxide concentration is excessively high, photosynthesis efficiency may decrease. Conversely, if the concentration is too low, it can also impact chlorophyll photosynthesis within chloroplasts. Research has demonstrated that for lettuce growth in controlled environments, an intercellular carbon dioxide concentration ranging from 500 to 1000 $\mu mol \cdot mol^{-1}$ is optimal, ensuring optimal plant growth and production. This experiment is conducted in a plant factory in an artificial environment, where the ambient carbon dioxide concentration is kept constant throughout the plant growth process. As depicted in Figure 6, it is evident that under different light quality ratios, the intercellular CO2 concentration of lettuce gradually decreased as the proportion of red light increased. The highest value, represented by the ratio R3B7, was 21%, 26.1%, and 31.8% higher than R7B3, R8B2, and R9B1, respectively. Numerous studies have established that CO2 concentration acts as a limiting factor for photosynthesis and the growth of many crops cultivated indoors [38]. Research by Park et al. [39] demonstrated a significant increase in photosynthetic rate with rising CO2 concentration. Moreover, CO2 concentration exhibited a negative correlation with the transpiration rate, indicating a decrease in transpiration rate with increasing CO2 concentration. This phenomenon can be attributed to the rise in CO2 concentration, which led to a reduction in stomatal conductance, aligning with the findings of the present experiment.

As shown in Figure 6, there are significant changes in the interactions between intercellular CO2 concentration, stomatal conductance, net photosynthetic rate, and transpiration rate under different light quality ratios. Notably, when the red light ratio exceeded the blue light ratio (R6B4, R7B3, R8B2), the net photosynthetic rate of the plants significantly increased compared to the combinations with a higher blue light ratio (R2B8, R3B7, R4B6). This increase in net photosynthetic rate resulted in a decrease in intercellular carbon dioxide concentration, triggering stomatal opening and an increase in leaf transpiration rate (Figure 6). These experimental results underscore the pivotal role of red light in lettuce photosynthesis. Indeed, red light is widely recommended as the essential spectrum for plant growth, whether in long-term or short-term cultivation scenarios [40]. Red light promotes aboveground elongation, enhances leaf number, width, area, plant height, aboveground fresh and dry weight [41], increases carbohydrate accumulation, and improves the carbon-to-nitrogen (C/N) ratio. Both chlorophyll and photosensitive pigments have absorption peaks in the red light band, making red light a potent driver of photosynthesis. Red light mediates the movement of chloroplasts by orienting their broadsides toward light through photosensitive pigments, affecting the capture of light energy. Additionally, red light influences the size and number of leaf stomata; for instance, chrysanthemums exhibit fewer stomata and larger stomatal areas under red light. Furthermore, red light affects photosynthesis by influencing RuBisCo activity. Research conducted by Du Shuang and colleagues on the photosynthetic properties of eggplant leaves revealed that under red light, the light absorption coefficient, apparent quantum yield, and maximum net photosynthetic rate of eggplant leaves are all higher than those under other monochromatic light treatments.

Simultaneously, stomatal conductance, transpiration rate, and the net photosynthetic rate of lettuce demonstrated a significant decrease under the light quality combination of R9B1, indicating the crucial role of blue light in the physiological processes of lettuce. Arcel, M. M. et al. [42] discovered that the combination of red and blue light resulted in a higher photosynthetic rate than pure red light. Additionally, leaf chlorophyll (chl) content increased with higher levels of blue light [43]. Blue light is directly sensed by phototropic pigments, activating plasma membrane ATPase to pump out protons continuously [44]. This process creates a transmembrane electrochemical gradient, promoting K+ uptake by the guard cells. Consequently, this reduces the intracellular osmotic potential, causing swelling of the

Figure 6
(a) Intercellular carbon dioxide concentration at different light qualities. (b) Net photosynthetic rate in different light qualities. (c) Stomatal conductance in different light qualities. (d) Transpiration rate under different light quality

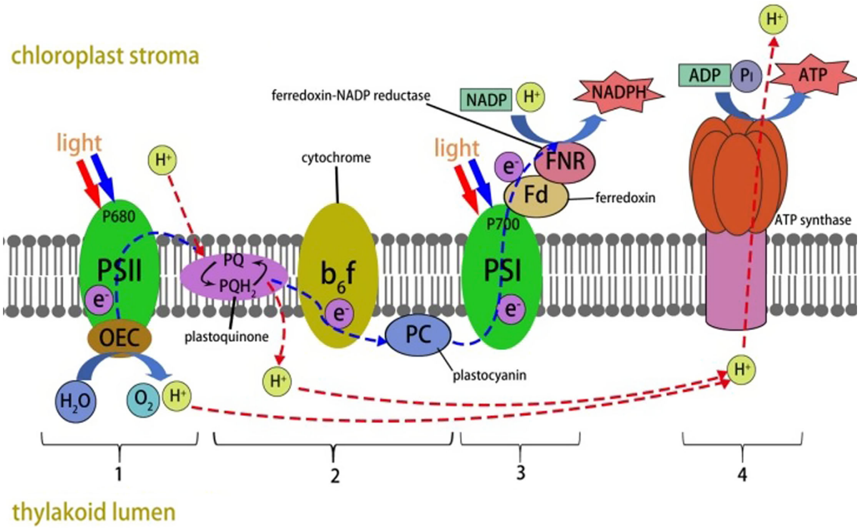


guard cells and rapid stomatal opening [45]. This effect leads to decreased resistance to CO2 diffusion. Blue light also influences leaf photosynthesis by modulating gene expression. The D1 protein plays a crucial role in the photosystem II (PSII) complex, which is a core component of the photosynthetic machinery in plants, algae, and cyanobacteria. It is integral to the light-dependent reactions of photosynthesis, where it participates in the process of water splitting and oxygen evolution [5].

Photosynthesis in plants comprises three essential processes: the primary reaction (involving light energy absorption, transfer, and conversion), electron transfer and photosynthetic phosphorylation, and carbon assimilation. Among these, the primary reaction and electron transfer/photosynthetic phosphorylation constitute the light reaction components. In photosynthesis, the photosystem acts as the functional unit for light energy absorption, consisting of the antenna complex and the reaction center complex. The pigments within the antenna complex, including most of the chlorophyll a and all the chlorophyll b, as well as carotenoids, are responsible for light energy absorption and transfer. When these pigments absorb light energy, they become excited states, and energy is transferred between them to the reaction center through resonance transfer. This energy transfer can occur between similar pigment molecules or between different pigment molecules. Energy transfer efficiency is remarkably high; for instance, carotenoids can transfer energy to chlorophyll a with an efficiency of up to 90%, and chlorophyll b can transfer energy to chlorophyll a with an efficiency close to 100%. Due to the organized arrangement of pigment molecules, energy transfer between different pigments follows a pattern where a pigment molecule with a shorter peak absorption wavelength transfers energy to a pigment molecule with a longer peak absorption wavelength, ultimately reaching the reaction center. The reaction center is a membrane protein complex in photosynthetic organisms that facilitates energy conversion during the light-dependent reactions of photosynthesis. It contains a specific chlorophyll a molecule essential for this process.

These chlorophyll molecules rapidly absorb light energy, inducing redox chemical changes, a process known as the photochemical reaction. This reaction constitutes the core step of photosynthesis, converting light energy directly into chemical energy, marking the end of the initial reaction. The content of chlorophyll directly affects the absorption and transfer of light energy and the photochemical reaction in plant photosynthesis. Experimental results demonstrate that when the red light ratio exceeded the blue light ratio, the SPAD values and net photosynthetic rate of lettuce (as indicated in Table 1 and Figure 6) were higher than in combinations with higher blue light ratios. This finding suggests that red light is more favorable for plants in the absorption and transfer of light energy and photochemical reactions, aligning with the results of the current study. Their arrangement and the steps of electron and proton transfer are illustrated in Figure 7. PSII hydrolysis releases hydrogen and releases oxygen. The electron transfer process in PSII can be divided into two parts: the first part involves hydrolysis to liberate oxygen before P680 excitation, and the second part involves electron transfer to PQ after P680 excitation, ultimately reaching PC. The cytochrome b6f complex is

Figure 7
Schematic diagram of the light system participating in plant growth



positioned between PSII and PSI, facilitating electron transfer through diffusible electron carriers. The function of the PSI complex is to transfer electrons from PC to ferredoxin. Photosynthetic phosphorylation utilizes light energy to drive electron transfer, establishing proton motive forces across the thylakoid membrane. These proton motive forces then synthesize ATP from ADP and inorganic phosphate. While red light can significantly enhance photosynthesis, an excessive amount of red light disrupts the balance between PSI and PSII. Blue light is necessary to maintain this balance. This also explains that the best physiological data of lettuce were obtained at the light quality ratio R8B2.

4. Conclusions

In summary, our study delved into the impact of different light quality ratios on lettuce growth and photosynthesis. Red light and blue light emerged as crucial players, each contributing significantly to the regulation of lettuce growth and development. The optimal balance between red and blue light proved pivotal, with our experimental results demonstrating that when the ratio of red light exceeded that of blue light, lettuce weight, dry matter content, and net photosynthetic rate were higher than treatments with a higher blue light ratio. This finding highlights the preference of lettuce for a higher ratio of red light, indicating its positive influence on lettuce growth. Notably, the most favorable growth and development were achieved at a light quality ratio of R8B2. At this ratio, lettuce weight, dry matter content, and net photosynthetic rate surpassed the lowest values by 27.5%, 13.9%, and 14.6%, respectively. Conversely, when the blue light ratio was too low (R9B1), lettuce weight and net photosynthetic rate decreased significantly by 27.5% and 9.1%, respectively, compared to the light quality combination of R8B2. This underscores the vital role of blue light in lettuce growth and development. In practical agricultural settings, it is advisable to utilize mixed light with a higher proportion of red light to irradiate lettuce. However, it is crucial to strike a balance, ensuring that the proportion of red light is not excessively high. This approach provides the most suitable growth environment for lettuce under artificial light conditions, maximizing its growth potential and overall productivity.

Funding Support

Shanghai Science and Technology Committee (STCSM) Science and Technology Innovation Program (Grant No. 23N21900100).

Shanghai Science and Technology Committee (STCSM) Science and Technology Innovation Program (Grant No. 22N21900400).

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Jun Zou: Conceptualization, Resources, Writing – review & editing, Supervision, Project administration. **Wenbin Liu:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Dawei Wang:** Methodology, Software, Data curation, Visualization. **Shipeng Luo:** Methodology, Software, Data curation, Visualization. **Yan Shen:** Validation, Resources, Data curation, Supervision. **Mingming Shi:** Conceptualization, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Hongliu Xu:** Resources, Project administration, Funding acquisition.

References

[1] Ilić, Z. S., & Fallik, E. (2017). Light quality manipulation improves vegetable quality at harvest and postharvest: A review. *Environmental and Experimental Botany*, *139*, 79–90. https://doi.org/10.1016/j.envexpbot.2017.04.006

[2] Paradiso, R., & Proietti, S. (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*(2), 742–780. https://doi.org/10.1007/s00344-021-10337-y

[3] Landi, M., Zivcak, M., Sytar, O., Brestic, M., & Allakhverdiev, S. I. (2020). Plasticity of photosynthetic processes and the accumulation of secondary metabolites in plants in response to monochromatic light environments: A review. *Biochimica et Biophysica Acta (BBA)-Bioenergetics*, *1861*(2), 148131. https://doi.org/10.1016/j.bbabio.2019.148131

[4] Vitale, E., Velikova, V., Tsonev, T., Ferrandino, I., Capriello, T., & Arena, C. (2021). The interplay between light quality and biostimulant application affects the antioxidant capacity and photosynthetic traits of soybean (Glycine max L. Merrill). *Plants*, *10*(5), 861. https://doi.org/10.3390/plants10050861

[5] Jin, D., Su, X., Li, Y., Shi, M., Yang, B., Wan, W., . . . , & Zou, J. (2023). Effect of red and blue light on cucumber seedlings grown in a plant factory. *Horticulturae*, *9*(2), 124. https://doi.org/10.3390/horticulturae9020124

[6] Ohtake, N., Ishikura, M., Suzuki, H., Yamori, W., & Goto, E. (2018). Continuous irradiation with alternating red and blue light enhances plant growth while keeping nutritional quality in lettuce. *HortScience*, *53*(12), 1804–1809. https://doi.org/10.21273/HORTSCI13469-18

[7] Kochetova, G. V., Avercheva, O. V., Bassarskaya, E. M., Kushunina, M. A., & Zhigalova, T. V. (2023). Effects of red and blue LED light on the growth and photosynthesis of barley (*Hordeum vulgare L.*) seedlings. *Journal of Plant Growth Regulation*, *42*(3), 1804–1820. https://doi.org/10.1007/s00344-022-10661-x

[8] Nguyen, T. K. L., Cho, K. M., Lee, H. Y., Cho, D. Y., Lee, G. O., Jang, S. N., . . . , & Son, K. H. (2021). Effects of white LED lighting with specific shorter blue and/or green wavelength on the growth and quality of two lettuce cultivars in a vertical farming system. *Agronomy*, *11*(11), 2111. https://doi.org/10.3390/agronomy11112111

[9] Xiao, L., Shibuya, T., Kato, K., Nishiyama, M., & Kanayama, Y. (2022). Effects of light quality on plant development and fruit metabolism and their regulation by plant growth regulators in tomato. *Scientia Horticulturae*, *300*, 111076. https://doi.org/10.1016/j.scienta.2022.111076

[10] Costine, B., Zhang, M., Pearson, B., & Nadakuduti, S. S. (2022). Impact of blue light on plant growth, flowering and accumulation of medicinal flavones in Scutellaria baicalensis and S. lateriflora. *Horticulturae*, *8*(12), 1141. https://doi.org/10.3390/horticulturae8121141

[11] Wang, P., Chen, S., Gu, M., Chen, X., Chen, X., Yang, J., . . . , & Ye, N. (2020). Exploration of the effects of different blue LED light intensities on flavonoid and lipid metabolism in tea plants via transcriptomics and metabolomics. *International Journal of Molecular Sciences*, *21*(13), 4606. https://doi.org/10.3390/ijms21134606

[12] Fan, X. X., Xue, F., Song, B., Chen, L. Z., Xu, G., & Xu, H. (2019). Effects of blue and red light on growth and nitrate metabolism in Pakchoi. *Open Chemistry*, *17*(1), 456–464. https://doi.org/10.1515/chem-2019-0038

[13] Wang, J., Lu, W., Tong, Y., & Yang, Q. (2016). Leaf morphology, photosynthetic performance, chlorophyll fluorescence, stomatal development of lettuce (*Lactuca sativa L.*) exposed to different ratios of red light to blue light. *Frontiers in plant science*, *7*, 250. https://doi.org/10.3389/fpls.2016.00250

[14] Gupta, Y. K., & Goel, A. (2023). EDFA controlled spectral efficient MIMO free space optic links for mitigation of climatic turbulence conditions. *Wireless Personal Communications*, *132*(4), 2563–2585. https://doi.org/10.1007/s11277-023-10732-6

[15] Gupta, Y. K., Goel, A., Tiwari, A., & Das, A. S. (2023). Performance analysis of high-speed MIMO FSO system in various data formats. In *2023 1st International Conference on Innovations in High Speed Communication and Signal Processing*, 398–401. https://doi.org/10.1109/IHCSP56702.2023.10127215

[16] Gupta, Y. K., & Goel, A. (2023). Performance analysis of multiple-beam WDM free space laser-communication system using homodyne detection approach. *Heliyon*, *9*(2), e13325. https://doi.org/10.1016/j.heliyon.2023.e13325

[17] Alrajhi, A. A., Alsahli, A. S., Alhelal, I. M., Rihan, H. Z., Fuller, M. P., Alsadon, A. A., & Ibrahim, A. A. (2023). The effect of LED light spectra on the growth, yield and nutritional value of red and green lettuce (*Lactuca sativa*). *Plants*, *12*(3), 463. https://doi.org/10.3390/plants12030463

[18] Kozai, T. (2013). Resource use efficiency of closed plant production system with artificial light: Concept, estimation and application to plant factory. Proceedings of the Japan Academy, Series B, 89(10), 447–461. https://doi.org/10.2183/pjab.89.447

[19] Chen, X. L., Li, Y. L., Wang, L. C., Yang, Q. C., & Guo, W. Z. (2022). Responses of butter leaf lettuce to mixed red and blue light with extended light/dark cycle period. *Scientific Reports*, *12*(1), 6924. https://doi.org/10.1038/s41598-022-10681-3

[20] Higashide, T. (2022). Review of dry matter production and growth modelling to improve the yield of greenhouse tomatoes. *The Horticulture Journal*, *91*(3), 247–266. https://doi.org/10.2503/hortj.UTD-R019

[21] Viršilė, A., Miliauskienė, J., Haimi, P. J., Laužikė, K., & Samuolienė, G. (2020). The comparison of constant and dynamic red and blue light irradiation effects on red and green leaf lettuce. *Agronomy*, *10*(11), 1802. https://doi.org/10.3390/agronomy10111802

[22] Wu, B. S., MacPherson, S., & Lefsrud, M. (2021). Filtering light-emitting diodes to investigate amber and red spectral effects on lettuce growth. *Plants*, *10*(6), 1075. https://doi.org/10.3390/plants10061075

[23] Song, J., Cao, K., Hao, Y., Song, S., Su, W., & Liu, H. (2019). Hypocotyl elongation is regulated by supplemental blue and red light in cucumber seedling. *Gene*, *707*, 117–125. https://doi.org/10.1016/j.gene.2019.04.070

[24] Novičkovas, A., Brazaitytė, A., Duchovskis, P., Jankauskienė, J., Samuolienė, G., Virsilė, A., . . . , & Zukauskas, A. (2010). Solid-state lamps (LEDs) for the short-wavelength supplementary lighting in greenhouses: experimental results with cucumber. In *XXVIII International Horticultural Congress on Science and Horticulture for People (IHC2010): International Symposium on 927*, 723–730. https://doi.org/10.17660/ActaHortic.2012.927.90

[25] Boros, I. F., Székely, G., Balázs, L., Csambalik, L., & Sipos, L. (2023). Effects of LED lighting environments on lettuce (*Lactuca sativa L.*) in PFAL systems–A review. *Scientia*

Horticulturae, *321*, 112351. https://doi.org/10.1016/j.scienta.2023.112351

[26] Voutsinos, O., Mastoraki, M., Ntatsi, G., Liakopoulos, G., & Savvas, D. (2021). Comparative assessment of hydroponic lettuce production either under artificial lighting, or in a Mediterranean greenhouse during wintertime. *Agriculture*, *11*(6), 503. https://doi.org/10.3390/agriculture11060503

[27] Sutulienė, R., Laužikė, K., Pukas, T., & Samuolienė, G. (2022). Effect of light intensity on the growth and antioxidant activity of sweet basil and lettuce. *Plants*, *11*(13), 1709. https://doi.org/10.3390/plants11131709

[28] Hernández, R., & Kubota, C. (2014). Growth and morphological response of cucumber seedlings to supplemental red and blue photon flux ratios under varied solar daily light integrals. *Scientia Horticulturae*, *173*, 92–99. https://doi.org/10.1016/j.scienta.2014.04.035

[29] Abedi, M., Tan, X., Stallknecht, E. J., Runkle, E. S., Klausner, J. F., Murillo, M. S., & Bénard, A. (2023). Incorporating the effect of the photon spectrum on biomass accumulation of lettuce using a dynamic growth model. *Frontiers in Plant Science*, *14*, 1106576. https://doi.org/10.3389/fpls.2023.1106576

[30] Liu, J., & van Iersel, M. W. (2022). Far-red light effects on lettuce growth and morphology in indoor production are cultivar specific. *Plants*, *11*(20), 2714. https://doi.org/10.3390/plants11202714

[31] Chen, D., Zhang, J., Sun, Z., Zhang, Z., & Hu, J. (2023). Multi-objective optimal regulation model and system based on whole plant photosynthesis and light use efficiency of lettuce. *Computers and Electronics in Agriculture*, *206*, 107617. https://doi.org/10.1016/j.compag.2023.107617

[32] Piovene, C., Orsini, F., Bosi, S., Sanoubar, R., Bregola, V., Dinelli, G., & Gianquinto, G. (2015). Optimal red: blue ratio in led lighting for nutraceutical indoor horticulture. *Scientia Horticulturae*, *193*, 202–208. https://doi.org/10.1016/j.scienta.2015.07.015

[33] Yan, Z., He, D., Niu, G., & Zhai, H. (2019). Evaluation of growth and quality of hydroponic lettuce at harvest as affected by the light intensity, photoperiod and light quality at seedling stage. *Scientia Horticulturae*, *248*, 138–144. https://doi.org/10.1016/j.scienta.2019.01.002

[34] Chen, X. L., & Yang, Q. C. (2018). Effects of intermittent light exposure with red and blue light emitting diodes on growth and carbohydrate accumulation of lettuce. *Scientia Horticulturae*, *234*, 220–226. https://doi.org/10.1016/j.scienta.2018.02.055

[35] Alsina, I., Erdberga, I., Duma, M., Alksnis, R., & Dubova, L. (2022). Changes in greenhouse grown tomatoes metabolite content depending on supplemental light quality. *Frontiers in Nutrition*, *9*, 830186. https://doi.org/10.3389/fnut.2022.830186

[36] Yudina, L., Sukhova, E., Mudrilov, M., Nerush, V., Pecherina, A., Smirnov, A. A., . . . , & Sukhov, V. (2022). Ratio of intensities of blue and red light at cultivation influences photosynthetic light reactions, respiration, growth, and reflectance indices in lettuce. *Biology*, *11*(1), 60. https://doi.org/10.3390/biology11010060

[37] Son, K. H., Lee, J. H., Oh, Y., Kim, D., Oh, M. M., & In, B. C. (2017). Growth and bioactive compound synthesis in cultivated lettuce subject to light-quality changes. *HortScience*, *52*(4), 584–591. https://doi.org/10.21273/HORTSCI11592-16

[38] Zhou, J., Li, P., & Wang, J. (2022). Effects of light intensity and temperature on the photosynthesis characteristics and yield of lettuce. *Horticulturae*, *8*(2), 178. https://doi.org/10.3390/horticulturae8020178

[39] Park, Y. G., Park, J. E., Hwang, S. J., & Jeong, B. R. (2012). Light source and CO 2 concentration affect growth and anthocyanin content of lettuce under controlled environment. *Horticulture, Environment, and Biotechnology*, *53*, 460–466. https://doi.org/10.1007/s13580-012-0821-9

[40] Kang, W. H., Park, J. S., Park, K. S., & Son, J. E. (2016). Leaf photosynthetic rate, growth, and morphology of lettuce under different fractions of red, blue, and green light from light-emitting diodes (LEDs). *Horticulture, Environment, and Biotechnology*, *57*, 573–579. https://doi.org/10.1007/s13580-016-0093-x

[41] Bian, Z., Yang, Q., Li, T., Cheng, R., Barnett, Y., & Lu, C. (2018). Study of the beneficial effects of green light on lettuce grown under short-term continuous red and blue light-emitting diodes. *Physiologia Plantarum*, *164*(2), 226–240. https://doi.org/10.1111/ppl.12713

[42] Arcel, M. M., Yousef, A. F., Shen, Z. H., Nyimbo, W. J., & Zheng, S. H. (2023). Optimizing lettuce yields and quality by incorporating movable downward lighting with a supplemental adjustable sideward lighting system in a plant factory. *PeerJ*, *11*, e15401. https://doi.org/10.7717/peerj.15401/supp-1

[43] Hwang, H., An, S., Lee, B., & Chun, C. (2020). Improvement of growth and morphology of vegetable seedlings with supplemental far-red enriched led lights in a plant factory. *Horticulturae*, *6*(4), 109. https://doi.org/10.3390/horticulturae6040109

[44] SharathKumar, M., Heuvelink, E., & Marcelis, L. F. (2020). Vertical farming: moving from genetic to environmental modification. *Trends in Plant Science*, *25*(8), 724–727. https://doi.org/10.1016/j.tplants.2020.05.012

[45] Quian-Ulloa, R., & Stange, C. (2021). Carotenoid biosynthesis and plastid development in plants: the role of light. *International Journal of Molecular Sciences*, *22*(3), 1184. https://doi.org/10.3390/ijms22031184

How to Cite: Zou, J., Liu, W., Wang, D., Luo, S., Shen, Y., Shi, M., & Xu, H. (2024). The Impact of Varying Ratios of Light Quality Emitted by Light-Emitting Diodes on the Butter Lettuce. *Journal of Optics and Photonics Research*. https://doi.org/10.47852/bonviewJOPR42024031