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RESEARCH ARTICLE
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Optimizing Growth of Crystal Lettuce Using Controlled Environments in a Thai Plant Factory

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ABSTRACT

The agricultural sector in Thailand faces significant challenges due to high summer temperatures reaching 40–43°C, which adversely affect plant growth and increase susceptibility to diseases. This study investigates the efficacy of using a Plant Factory with Artificial Lighting (PFAL) to optimize the growth conditions for Crystal Lettuce, aiming to enhance plant development and yield under controlled environments. The research focuses on determining the ideal environmental parameters within a PFAL to maximize the growth of Crystal Lettuce. Crystal Lettuce seeds were initially grown in cups filled with a perlite-vermiculite mix (3:1) and a nutrient solution with an electrical conductivity (EC) of 1400–1600µS/cm and pH of 5.5–6.2. These seedlings were exposed to white LED lights with an intensity of 17750Lux for 10 hours daily. After initial growth, the seedlings were transplanted into a nutrient solution with an EC of 1750–1830µS/cm and subjected to yellow-white LED lights. The grow room, covering 160m^2, maintained a controlled temperature of 30°C, humidity at 71%, and CO_2 levels between 876–942ppm. Light intensity across different planting layers ranged from 7474 to 25722Lux. Results demonstrated that Crystal Lettuce plants in the middle of the planting layer, receiving approximately 23691Lux, exhibited the most significant growth, with a plant height of 18.75cm, fresh weight of 91.50g, and canopy width of 22.00cm. In contrast, plants on the edges with lower light intensities showed reduced growth. The study concludes that controlled environmental conditions in a PFAL, particularly optimized light intensity, substantially improve the growth of Crystal Lettuce. This research supports the potential of PFAL systems to enhance agricultural productivity in regions with challenging climates.

Keywords: Crystal Lettuce, Plant Factory with Artificial Lighting (PFAL), Controlled Environment Agriculture, Hydroponics, Light Intensity Optimization

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INTRODUCTION

Thailand's agricultural sector faces significant challenges due to its tropical climate, characterized by extreme temperatures and erratic weather patterns (Lilavanichakul and Pathak, 2024). Recent data indicate summer temperatures reaching 40–43°C, accompanied by seasonal storms, prolonged droughts, and other climate change impacts (Thai Meteorological Department, 2023). These environmental stressors severely impede optimal plant growth, increase phytopathological issues, and necessitate increased agrochemical use, leading to

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concerns about chemical residues in produce. The agricultural challenges are further exacerbated by a declining workforce and diminishing arable land, creating an urgent need for innovative solutions to enhance productivity and resilience in the face of climate change (Phasinam et al., 2022). Controlled environment agriculture, particularly Plant Factories with Artificial Lighting (PFAL), has emerged as a promising approach to address these issues (Kozai and Niu, 2020a, 2020b).

Environmental factors play a crucial role in plant growth and development. Carbon dioxide (CO_2) concentration, temperature, and light are among the most critical factors influencing plant physiology and productivity. Optimal CO_2 levels and air movement are essential for efficient photosynthesis (Pukpakdee, 1998). Temperature significantly affects metabolic activities and physiological processes, with each species having specific optimal ranges (Ducruet, 2007). Elevated temperatures can cause irreversible cellular damage, impair photosynthetic machinery, and trigger programmed cell death in plants (Mondal et al., 2023; Lemke et al., 2024).

Light serves as a fundamental energy source indispensable for driving the photosynthetic processes vital for plant development and growth. However, excessive light exposure, coupled with the absorption of ultraviolet radiation, can induce light stress in plants, precipitating the generation of free radicals and subsequent cellular damage. Approximately 47% of solar irradiance reaches the Earth's surface, with the remaining portion being dissipated through atmospheric reflection and scattering (Larcher, 1983; Larcher, 2003). Atmospheric light intensity registers at approximately 1.39kWm^{-2}, exhibiting wavelengths spanning from 290 to 105nm. Shorter wavelengths are absorbed by atmospheric constituents such as ozone and oxygen, while longer wavelengths are attenuated by water vapor and carbon dioxide. Roughly 45% of solar energy falls within the 400–700nm wavelength range, known as photosynthetically active radiation (PAR), indispensable for photosynthesis, and perceptible as visible light to the human eye. PAR can be quantified in terms of energy (Wm^{-2}) or quantum flux (mol m^{-2}s^{-1}) (McCree, 1981). Light below the PAR threshold is categorized as ultraviolet radiation, comprising UV-A (315–380nm) and UV-B (290–315nm) spectra, while light beyond PAR is classified as infrared radiation (750–4000nm), predominantly utilized in the photosynthetic process. Chlorophyll serves as the primary photoreceptor in green plants, predominantly absorbing red and blue light wavelengths. Additional pigments such as carotenes and xanthophylls complement chlorophyll by absorbing blue and ultraviolet light. Red and blue algae utilize distinct pigments, including phycocyanin and phycoerythrin, to harness light energy for photosynthesis (Purves et al., 1995).

PFAL systems offer precise control over these environmental factors, potentially mitigating the challenges posed by Thailand's climate. These systems involve cultivating plants in enclosed environments with artificial lighting, typically using LED technology, and precise regulation of temperature, humidity, and nutrient delivery (National Electronics and Computer Technology Center, 2023). Recent advancements in PFAL technology, particularly in LED lighting, have significantly improved their efficiency and effectiveness (Kozai, 2019).

The paradigm of LED-based cultivation, often referred to as PFAL, has witnessed substantial development primarily in Japan and various Asian nations including Taiwan, China, and Singapore, as well as in the United States and Europe. These advancements are characterized by scalability enhancements and the integration of cutting-edge technologies such as automation and artificial intelligence, aimed at further optimizing PFAL systems (Hayashi, 2020). LED lighting plays a crucial role in PFAL systems, offering unprecedented control over light spectrum and intensity. Pennisi et al. (2019) demonstrated that manipulating the red:blue ratio in LED lighting can significantly affect resource use efficiency and nutritional quality in indoor lettuce cultivation. Park and Runkle (2017) further showed that incorporating far-red radiation can promote seedling growth by increasing leaf expansion and whole-plant net assimilation (Ries and Park, 2024). Additionally, Hasan et al. (2017) reported that LED lighting could enhance the accumulation of various phytochemicals in plants, potentially improving their nutritional value and health benefits.

The potential of PFAL systems extends beyond just mitigating environmental challenges. Shamshiri et al. (2018) highlighted the role of smart greenhouse technology, including PFAL, in optimizing plant growth and resource use efficiency. These systems have shown promising results in enhancing crop yield and quality while reducing environmental impact. For instance, Veremeichik et al. (2023) reported a twenty-fold increase in flavonol production in *Eruca sativa* (arugula) under LED lighting compared to conventional sources. Similarly, investigations into lettuce (*Lactuca sativa* L "Greenwave") cultivation under combined blue, green, and red LED lighting regimes have revealed noteworthy impacts on photosynthetic efficiency, growth dynamics, and morphological attributes. Notably, the application of monochromatic red and blue light sources influenced stem elongation, whereas the incorporation of fluorescent lighting resulted in augmented fresh weight (Shimizu et al., 2011).

Given the multifaceted benefits of PFAL systems in providing precisely tailored growth environments, this study aims to optimize conditions for Crystal Lettuce growth in a controlled environment. By leveraging artificial lighting technologies and environmental control, we seek to develop a proactive strategy for addressing contemporary agricultural challenges in Thailand, potentially offering a model for sustainable agriculture in regions facing similar climatic challenges.

MATERIALS & METHODS

Planting and Growth Conditions

Crystal Lettuce (*Lactuca sativa*) seeds were selected for this study due to their popularity and sensitivity to environmental conditions. The seeds were initially sown in cups filled with a perlite-vermiculite mix in a 3:1 ratio. This medium was chosen for its excellent aeration and water retention properties, providing an optimal starting environment for seed germination and early growth.

Nutrient Solution

The seedlings were first grown in a nutrient solution with an electrical conductivity (EC) of 1400–1600µS/cm and a pH range of 5.5–6.2. This initial phase lasted until the seedlings developed a robust root system. Subsequently, the seedlings were transplanted to a more nutrient-rich solution with an EC of 1750–1830µS/cm, maintaining the same pH range to ensure consistent nutrient availability and uptake.

Lighting Conditions

Throughout the growth cycle, the seedlings were exposed to white LED lights with an intensity of 17750Lux for 10 hours daily during the initial growth phase. After transplantation, they were subjected to yellow-white LED lights. Light intensity was carefully controlled and varied across different planting layers, ranging from 7474 to 25722Lux, to assess its impact on plant growth. The lights were positioned to provide uniform illumination, with specific attention to ensuring consistent exposure for all plants.

Grow Room Setup

The study was conducted in a grow room measuring 160m^2, equipped with a Nutrient Film Technique (NFT) hydroponic system. This facility accommodates five rows of planting shelves, each comprising seven levels, with dimensions of 155 x 604 x 305cm (width x length x height) and inter-floor spacing set at 50cm. A planting rail measuring 10x604cm (width x length) is affixed within each layer, supporting a total of nine rails spaced 7cm apart, featuring planting orifices spaced at 20cm intervals. Each floor accommodates 270 planting apertures. White-yellow LED light fixtures, measuring 2.5 x 120 x 3.5cm (width x length x height), are strategically positioned alongside the planting layers, mounted at a height of 24cm from the rails, with a spacing of 15cm between each fixture. A nutrient reservoir is situated beneath the planting layers, containing 325 liters of nutrient solution per row (Fig. 1). Carbon dioxide supplementation within the cultivation environment is regulated within a range of 876–942 parts per million (ppm), maintaining a temperature of approximately 30°C, relative humidity at approximately 71%, and ensuring a light intensity ranging from 7474 to 25722Lux incident upon the planting rails (Fig. 2). These conditions were chosen based on preliminary studies indicating optimal growth rates for lettuce.

Experimental Design

The experimental setup included multiple planting rails arranged in layers. LED lights were installed at specific heights and intervals to ensure uniform light distribution. Plants were systematically positioned within the grow room to receive varying light intensities, enabling the study of light's effect on growth. Regular monitoring and adjustments were made to maintain the desired environmental conditions.

Fig. 1: Wangree resort's plant factory: Illuminated growth.

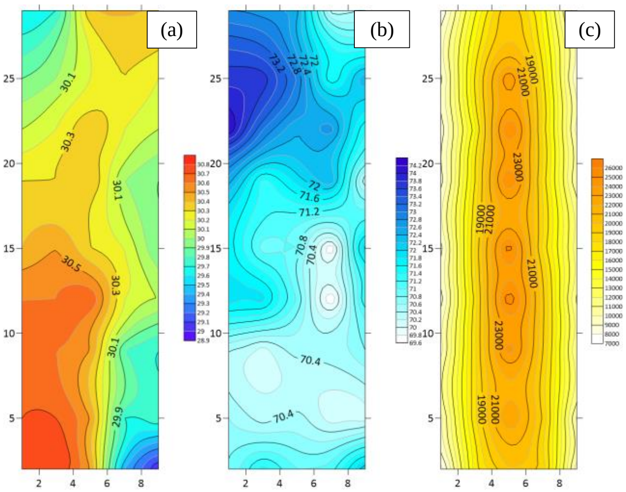

Fig. 2: Environmental factors in growing layers; (a) Temperature. (b) Relative humidity. (c) Light intensity.

Data Collection and Analysis

Experimental results were recorded through a systematic protocol, whereby one week post-transplantation of Crystal Lettuce, three plants were randomly selected from each trough for analysis. Subsequent measurements encompassed the plant's height and total fresh weight, inclusive of the planting cup. Upon reaching the 28-day mark post-transplantation, the entire planting cup was harvested, and comprehensive data on plant height, canopy width, and total fresh weight, including the planting cup, were documented. The experimentation period spanned from February to March 2023 and was conducted at Seminar Park Co., Ltd. (Wangree Resort), located at 143 Moo 12 Tambon Khaophra, Amphur Muang, Nakhon Nayok, Thailand. Data collection and analysis procedures involved continuous monitoring of plant growth parameters, namely height, fresh weight, and canopy width, at predetermined intervals. Analysis encompassed plants positioned at varying locations within the cultivation environment to assess the impact of light intensity gradients on growth metrics, with statistical methodologies employed to ascertain significant differences across distinct light exposure levels and environmental contexts.

RESULTS & DISCUSSION

This study investigated the growth of Crystal Lettuce in a Nutrient Film Technique (NFT) system under controlled environmental conditions. The system utilized white-yellow LED lighting for 10 hours daily, with electrical conductivity (EC) ranging from 1750 to 1830µS/cm and pH maintained between 5.5 and 6.2. The greenhouse environment was characterized by a consistent temperature of 30°C, relative humidity of 71%, and CO_2 levels between 876–942ppm. Our findings reveal a significant correlation between light intensity and plant growth parameters. Optimal growth was observed in the middle tier of the planting layers (rail 5), where light intensity measured approximately 23691Lux. Here, plants exhibited the highest growth metrics: 18.75cm in height, 91.50g fresh weight, and 22.00cm canopy width. In contrast, plants on the right (rail 8, 9831Lux) and left (rail 2, 8602Lux) sides of the planting layer showed reduced growth, with heights of 16.75cm and 16.50cm, fresh weights of 69.00g and 58.00g, and canopy widths of 19.00cm and 18.00cm, respectively (Fig. 3–5).

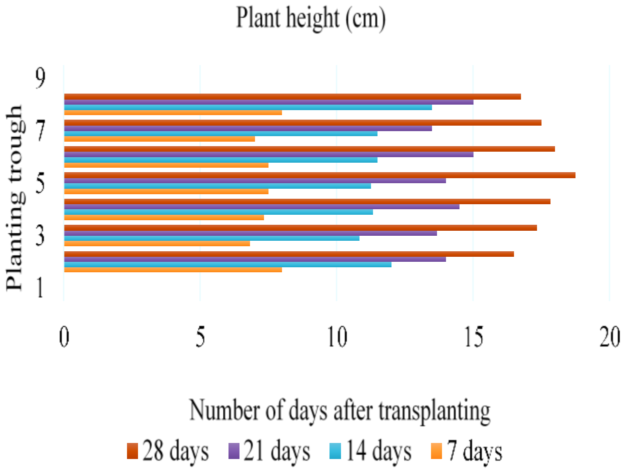

Fig. 3: Vertical growth dynamics: Plant height variation

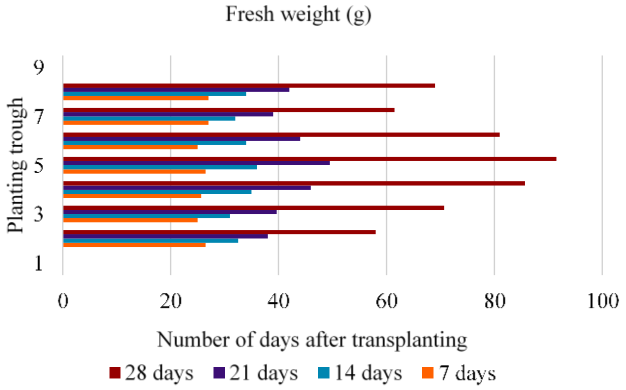

Fig. 4: Total biomass: Fresh weight of entire plant with cup

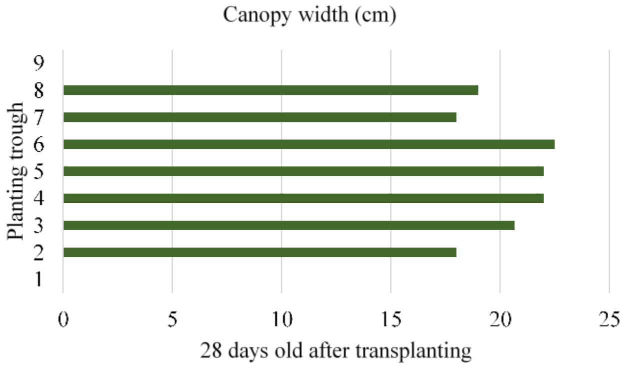

Fig. 5: Expanding canopy: Measurement of canopy width

These findings are consistent with prior research, including Esmaili et al. (2021), which demonstrated improvements in lettuce growth metrics with increased light intensity. Similarly, Yan et al. (2019) reported enhanced growth and quality in lettuce cultivated under higher light intensities, supporting our observations. However, Sutulienė et al. (2022) highlighted a complex relationship between light intensity and antioxidant capacity, indicating the necessity for further investigation into how light intensity affects both nutritional quality and growth parameters. The superior growth observed under controlled LED lighting conditions in our study supports the findings of Rittiram and Tira-umphon (2019), who reported enhanced lettuce growth under LED lighting compared to outdoor cultivation. This underscores the potential of PFAL systems to boost agricultural productivity in regions with challenging climates, such as Thailand. However, optimizing light conditions extends beyond intensity alone. Son and Oh (2013) demonstrated that light quality significantly affects not only growth but also phytochemical content and antioxidant capacity of lettuce in PFAL systems. They found that red and blue LED combinations were particularly effective in enhancing both growth and nutritional quality (Razzak et al., 2022). Similarly, Tarakanov et al. (2022) showed that spectral composition significantly influences lettuce biomass, quality, and production efficiency in plant factory settings. The implications of our findings extend beyond lettuce cultivation. Viršilė et al. (2017) reviewed the use of LED lighting in horticulture and highlighted its potential for a wide range of crops. They emphasized the need for crop-specific lighting recipes to optimize growth and quality, suggesting that our approach could be adapted for other high-value crops suitable for PFAL cultivation in Thailand. While our results are promising, it's crucial to consider the broader implications of PFAL implementation. Kozai (2019) points out that the sustainability of PFAL systems depends on various factors, including energy efficiency and resource use. Future research should focus on optimizing these aspects to ensure the long-term viability of PFAL in Thailand's agricultural sector. The potential of PFAL systems to mitigate the impacts of climate change on agriculture is significant. Huan et al. (2010) demonstrated that different LED light qualities can affect not only plant growth but also leaf anatomy and chloroplast ultrastructure in lettuce. This suggests that PFAL systems could potentially be used to 'climate-proof' crops by optimizing their physiological development under controlled conditions. Furthermore, the interaction between light conditions and other environmental factors should not be overlooked. Khan et al. (2018) investigated the effects of light quality on lettuce growth under different nitrate concentrations, finding that optimal light conditions varied depending on nutrient availability. This highlights the importance of an integrated approach to environmental control in PFAL systems.

In conclusion, our study contributes to the growing body of evidence supporting the potential of PFAL systems to enhance agricultural productivity and sustainability, particularly in challenging climates like Thailand's. The observed optimal light intensity of approximately 23691Lux for Crystal Lettuce growth provides a valuable reference point for PFAL operations. However, further research is needed to optimize these systems for a wider range of crops and to ensure their economic and environmental sustainability in the long term. Future studies should focus on refining light recipes, investigating the interplay between light and other environmental factors, and assessing the nutritional quality of PFAL-grown produce.

Conclusion

This study confirms that using a Plant Factory with Artificial Lighting (PFAL) can significantly enhance the growth of Crystal Lettuce by providing a controlled environment that mitigates the adverse effects of extreme temperatures common in Thailand. The findings demonstrate that optimal light intensity, along with carefully managed temperature, humidity, and CO_2 levels, are crucial for maximizing the growth and yield of Crystal Lettuce. Plants exposed to higher light intensities, particularly around 23691Lux, showed superior growth metrics in terms of height, fresh weight, and canopy width compared to those under lower light intensities. The ability to maintain consistent environmental conditions within the PFAL system offers a substantial advantage over traditional farming methods, which are often hampered by unpredictable weather and extreme temperatures.

Recommendation

Further research should explore the applicability of these findings to other crops and investigate additional environmental variables that could further optimize growth within PFAL systems.

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Conflict of Interest

The authors declare no conflict of interest.

Author's Contribution

Phraomas Charoenrak: Conceptualization; data curation; writing–original draft; formal analysis; methodology; resources. Dowroong Watcharinrat: Project administration; resources; supervision; validation; visualization. Kiatsuda Suvanapa: Investigation; formal analysis; methodology; validation. Nikorn Saengngam: Investigation; validation. Suwonnakan Supamattra: Data Curation; resources; visualization. Thanwamas Phasinam: Investigation; validation. Khongdet Phasinam: Conceptualization; investigation; validation; visualization; writing–review and editing.

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