

Effects of Ultraviolet Light Exposure Duration on the Leaf Development of Pak-choi (*Brassica rapa* L. subsp. *chinensis*) Grown in a Greenhouse Tower Hydroponic System

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ABSTRACT

The increasing demand for sustainable vegetable production has encouraged the adoption of greenhouse hydroponic systems integrated with supplemental lighting technologies. This study evaluated the effects of different ultraviolet (UV) light exposure durations on the leaf development of pak-choi (*Brassica rapa* L. subsp. *chinensis*) grown in a greenhouse tower hydroponic system. A completely randomized design (CRD) with five treatments and three replications was employed: T1–Control (natural light), T2–UV light at 30 cm for 4 hours, T3–UV light at 30 cm for 8 hours, T4–UV light at 50 cm for 4 hours, and T5–UV light at 50 cm for 8 hours. The leaf number and leaf area were measured at 10, 20, and 30 days after transplanting (DAT), and the data were analyzed using analysis of variance (ANOVA) followed by Tukey's Honest Significant Difference (HSD) test. Results showed that T3 consistently produced the highest leaf number (5.63, 7.43, and 12.30) and the largest leaf area (31.40, 51.37, and 118.97 cm²) across all observation periods, while the control treatment recorded the lowest values. The findings indicate that an 8-hour UV exposure at a 30 cm distance significantly enhanced the vegetative growth of pak-choi under greenhouse hydroponic conditions. This study demonstrates that optimizing UV light exposure duration can improve crop productivity and supports sustainable protected agriculture by contributing to Sustainable Development Goals 2 (Zero Hunger), 12 (Responsible Consumption and Production), and 13 (Climate Action).

1 INTRODUCTION

As the world's population continues to grow and more people move to cities, the demand for food is increasing, which puts a lot of pressure on farming. However, with climate change, land degradation, and water scarcity, traditional farming faces major challenges. Therefore, we must explore new and sustainable ways to farm (Dutta et al., 2025; Şimşek, 2025). Controlled environment agriculture (CEA), such as greenhouses and hydroponics, is stepping up as a great way to grow crops year-round while using resources more efficiently (Alrajhi et al., 2023; Azizi et al., 2025). In addition, using artificial lighting, especially ultraviolet (UV) light, is key to helping plants grow and boosting crop yields (Azizi et al., 2025; Zandi et al., 2022). These innovations are crucial for achieving

SDG 2 (Zero Hunger) by increasing food production, SDG 12 (Responsible Consumption and Production) by using resources wisely, SDG 13 (Climate Action) by encouraging sustainable farming, and SDG 9 (Industry, Innovation, and Infrastructure) by promoting agricultural technology (Abbasi & Zhang, 2024; Rahman et al., 2025; Şimşek, 2025). In addition, precision agriculture and IoT-based farming are making it easier to monitor, automate, and boost productivity, helping make farming systems more sustainable and resilient (Dutta et al., 2025; Nath, 2023; Thobane et al., 2025).

In the Philippines, there is a growing demand for vegetables, but with limited agricultural land and climate challenges, farmers have turned to greenhouse and hydroponic farming systems. Pak-choi, also known as *Brassica rapa* subsp. *chinensis*, is a standout leafy vegetable because it is packed with nutrients and has

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significant economic value (Lillo et al., 2025; Parreño, 2023). By adding supplemental LED and UV lighting in these controlled environments, crop productivity has improved (Nirbita et al., 2024; Rehman et al., 2024). These methods help achieve several Sustainable Development Goals: boosting vegetable production for SDG 2, enhancing water and nutrient efficiency for SDG 12, supporting climate-resilient agriculture for SDG 13, and driving technological innovation in protected farming for SDG 9 (Lillo et al., 2025; Philip & G, 2024).

Light plays a crucial role in the growth and development of pak-choi. Research indicates that UV-A radiation can enhance leaf expansion, photosynthesis, biomass accumulation, and antioxidant production when applied under suitable conditions (Xu et al., 2024; Viršilė et al., 2023; Zandi et al., 2022). However, it is important to note that excessive UV exposure may lead to plant stress and hinder growth, making it essential to optimize the duration of UV exposure for greenhouse production (Niculcar et al., 2023; Onur et al., 2025). Additionally, vertical hydroponic systems maximize space, improve water and nutrient efficiency, and support sustainable urban agriculture, while IoT-based technologies enable precise environmental monitoring and lighting control (Găgeanu et al., 2024; Hutchinson et al., 2025; Aranda Barrera & Ponce, 2025; Hatipi et al., 2024; Suheri et al., 2024). These innovations contribute to strengthening SDG 2, SDG 9, SDG 12, and SDG 13 by promoting efficient, innovative, and climate-smart agricultural production (Abbasi & Zhang, 2024; Nirbita et al., 2024; Philip & G, 2024; Şimşek, 2025). Despite these advances, most previous studies have concentrated on UV wavelength, light quality, and intensity, while the duration of UV exposure, particularly in greenhouse tower hydroponic systems, has received limited attention. Few studies have simultaneously evaluated leaf number and leaf area under different UV exposure durations, and local evidence for greenhouse vegetable production in the Philippines remains limited. Therefore, this study aimed to determine the effects of different durations of ultraviolet light exposure on the leaf development of pak-choi grown in a greenhouse tower hydroponic system. The findings are expected to provide practical recommendations for optimizing supplemental UV lighting and supporting sustainable greenhouse vegetable production.

2 MATERIALS AND METHODS

Experimental Site

The study was conducted in a greenhouse at the College of Agriculture, Isabela State University, Echague, Isabela.

Seed and Nutrient Preparation

Pak-choi seeds were germinated in horticultural foam soaked in water for at least 12 h before sowing. The seeds began to germinate 24 hours after sowing.

Pak-choi seedlings were transplanted into the tower hydroponic system once they developed 3–4 leaves.

The nutrient solution was prepared by mixing 2.5 ml of a nitrogen-based plant nutrient solution with 1 liter of unchlorinated water. The pH level was measured and continuously monitored using a pen-type pH meter. When required, a buffer solution (pH up or pH down) was used to adjust the pH to the optimum range of 6.0–7.0 for pak-choi.

Establishment of THS and installation of UV lights

A tower hydroponic system was established within a chamber inside the greenhouse. Hydroponic towers, each able to support 75 seedlings and with a 16-liter base reservoir, were commercially purchased.

UV lights were mounted on each tower at 30 cm and 50 cm from the tower. The UV light intensities were 2600–2700 lux and 1700–1800 lux at distances of 30 cm and 50 cm, respectively. Digital timers were installed to automate the UV light exposure duration of each treatment.

Experimental Design

The study was laid out in a completely randomized design (CRD) with five treatments and three replications. The experimental treatments were as follows: T1 – Control (natural light); T2 – UV light at 30 cm distance exposed for 4 hours; T3 – UV light at 30 cm distance exposed for 8 hours; T4 – UV light at 50 cm distance exposed for 4 hours; and T5 – UV light at 50 cm distance exposed for 8 hours.

Data Gathering

Data on the number of leaves and leaf area of pakchoi were gathered at 10, 20, and 30 days after transplanting. These parameters are important leaf indices related to plant growth and development. The number of leaves (NL) was gathered by counting every visible leaf per plant sample. The leaf area (LA) was calculated using the Montgomery equation, $LA (cm^2) = kLW$, where LW is the leaf length (cm) and width (cm) of Pak-choi and k is the correction factor. Leaf length was measured from the lamina tip to the intersection of the lamina and petiole along the lamina midrib; leaf width was measured from tip to tip between the widest lamina lobes (Ding *et al.*, 2022). The correction factor employed in this study was 0.67 because Pak-choi leaves are oval or obovate (Schrader *et al.*, 2021).

Data Analysis

The collected data were analyzed using the Statistical Tool for Agricultural Research (STAR) application developed by the International Rice Research Institute (IRRI). The results were interpreted and discussed accordingly.

3 RESULTS AND DISCUSSION

3.1 Number of Leaves.

Table 1 shows that pak-choi plants exposed to UV light at a distance of 30 cm for 8 hours (T3) consistently produced the highest number of leaves at 10, 20, and 30 days after transplanting, while the control treatment (T1) recorded the lowest values. These results indicate that longer UV exposure promoted better vegetative growth than shorter exposure periods, particularly when the light source was closer to the plants. This suggests that an appropriate duration of UV light enhances leaf development by improving photosynthesis and other physiological processes that support plant growth. These findings are consistent with previous studies reporting that controlled UV-A exposure stimulates leaf development, biomass accumulation, and overall plant productivity under controlled environments (Zandi et al., 2022; Viršilė et al., 2023; Azizi et al., 2025). Likewise, Gao et al. (2022) found that longer supplementary UV-A exposure resulted in greater vegetative growth than shorter exposure periods. The low coefficients of variation further indicate that the experimental results were reliable and consistent, demonstrating that 8-hour UV exposure at 30 cm is the most effective treatment for promoting leaf production in greenhouse-grown hydroponic pak-choi.

Table 1. Number of Leaves (NL) of Pak-choi as affected by varying UV distances and exposure duration

Treatments	NL at 10 DAT	NL at 20 DAT	NL at 30 DAT
T1 – Control (Natural light)	5.20b	6.07d	9.40c
T2 – UV light at 30 cm distance exposed for 4 hours	5.40ab	6.70c	10.37b
T3 – UV light at 30 cm distance exposed for 8 hours	5.63a	7.43a	12.30a
T4 – UV light at 50 cm distance exposed for 4 hours	5.23b	6.93bc	11.03b
T5 – UV light at 50 cm distance exposed for 8 hours	5.53a	7.23ab	11.27ab
CV (%)	2.48	3.46	4.69

Means with the same letter are not significantly different using Tukey's Honest Significant Difference (HSD) Test

3.2 Leaf Area

Table 2 shows that pak-choi plants exposed to UV light at a distance of 30 cm for 8 hours (T3) consistently produced the largest leaf area at 10, 20, and 30 days after transplanting, while the control treatment (T1) recorded the smallest leaf area throughout the study.

These results indicate that longer UV exposure and a shorter distance from the light source promoted greater leaf expansion than the other treatments. A larger leaf area enhances the plant's ability to capture light for photosynthesis, resulting in improved vegetative growth. These findings agree with previous studies showing that controlled UV-A exposure stimulates leaf expansion, photosynthetic efficiency, and biomass accumulation in leafy vegetables grown under controlled environments (Zandi et al., 2022; Viršilė et al., 2023; Azizi et al., 2025). Similarly, Klongdee et al. (2024) reported that optimized UV light application enhanced plant growth, while Nam et al. (2025) emphasized that precise light management improves crop development and productivity in protected cultivation. The low coefficients of variation indicate that the results were consistent and reliable, suggesting that an 8-hour UV exposure at 30 cm was the most effective treatment for increasing the leaf area of greenhouse-grown hydroponic pak-choi.

Table 2. Leaf area (LA) of Pak-choi at 10, 20 and 30 days after transplanting

Treatments	LA at 10 DAT, cm	LA at 20 DAT, cm	LA at 30 DAT, cm
T1 – Control (Natural light)	21.26c	37.29c	83.84d
T2 – UV light at 30 cm distance exposed for 4 hours	26.89b	44.93b	103.00c
T3 – UV light at 30 cm distance exposed for 8 hours	31.40a	51.37a	118.97a
T4 – UV light at 50 cm distance exposed for 4 hours	27.18b	45.15b	103.56bc
T5 – UV light at 50 cm distance exposed for 8 hours	29.24ab	49.27a	113.41ab
CV (%)	4.69	3.29	3.63

Means with the same letter are not significantly different using Tukey's HSD test

4 CONCLUSION

Based on the findings of the study, the results indicated that the duration of exposure to ultraviolet (UV) light had a substantial effect on the leaf development of pak-choi cultivated in a tower hydroponic system under greenhouse conditions. The study achieved its goal of measuring the effects of varied lengths of UV light exposure on leaf area and leaf number. In the treatments tested, the application of UV light at 30 cm distance for 8 hours (T3) always

showed the largest leaf area and the highest number of leaves during the observation period. The lowest values for both parameters were found in plants cultivated under natural light only.

Results indicated that vegetative development improved when the exposure time to UV radiation increased from 4 to 8 hours, especially when the light source was placed closer to the plants. The results show that the best combination of UV light intensity and exposure time promotes leaf expansion and leaf production, which leads to better plant growth. Therefore, 8 h of additional UV illumination at 30 cm may be suggested as an efficient lighting approach to optimize the vegetative growth of greenhouse tower

hydroponic pak-choi. Additional research is needed to understand the impact of UV light on other growth, yield, and quality characteristics, as well as to identify the optimal UV wavelength and exposure regime for commercial hydroponic cultivation.

Compliance with ethical standards

This study was conducted to evaluate the effects of UV light on the growth of pak-choi grown in a tower hydroponics system within a greenhouse setting. The study did not involve human participants or animals and was carried out in accordance with established agricultural research protocols and methodological procedures.

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