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Maximising Growth and Quality of *Caulerpa lentillifera* Through Multilevel Cultivation with LED Approach

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ABSTRACT

Caulerpa lentillifera (Laktud) is an edible green macroalga with increasing relevance in food and aquaculture. At the Kubang Badak cultivation site in Langkawi, the use of pond space is constrained by uneven light distribution across vertically arranged growing levels. This study evaluated a multilevel cultivation arrangement under white LED, pink LED and natural sunlight over 28 days. Nine cultivation plates were used, with three plates assigned to each lighting condition. Frond density, frond length, plate weight, daily growth rate (DGR) and biomass yield were recorded. At Week 4, plate W2 had the highest recorded frond density (79.33 per 100 cm²) and plate weight (1,305 g); it also had the highest reported DGR (0.018551 day^{-1}) and biomass yield (247.76 g m^{-2} day^{-1}). The longest individual fronds were recorded on sunlight-exposed plate S1 (4.628 cm), followed by white-LED plate W3 (4.017 cm). In contrast, frond density on S3 declined to 3.67 per 100 cm². The results indicate that LED lighting may help improve growth consistency across multilevel cultivation plates, although the sunlight treatment showed substantial variation among shelf positions. Further replicated experiments with measured photosynthetically active radiation and controlled shelf positions are needed to confirm the treatment effects and optimise the system for practical cultivation.

Keywords: Biomass yield, *Caulerpa lentillifera*, daily growth rate, frond density, growth multilevel cultivation

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INTRODUCTION

The development of Caulerpa seaweed holds enormous promise in a variety of industries, including food, biotechnology, and environmental conservation, yet it remains understudied in Malaysia. According to a recent study by Phang et al. (2019), Malaysian seaweeds are becoming more diverse, and the Langkawi Islands are flowering with Caulerpa species. The same study stated that the increasing seaweed diversity in Malaysia is indirectly making Langkawi Island a center for several Caulerpa species. According to Phang et al. (2005), around 84 taxa of seaweeds have been identified on Langkawi Island. The species are *Padina (Phaeophyta), Halimeda, Caulerpa, Bryopsis (Chlorophyta), Gracilaria, Acanthophora, Asparagopsis, Polysiphonia,* and *Hypnea (Rhodophyta).* According to Sinurat and Fadjriah (2019), this species thrives by attaching itself to rock fragments or sand substrates. However, Zuldin et al. (2019) point out that a lack of study on cultivation methods makes it difficult for local communities to benefit from Caulerpa production. Wild stock availability is severely strained as a result of intense harvesting practices that exacerbate the strain on wild stocks (Nagappan & Vairappan, 2014). Cultivating Laktud has provided many residents with a source of income and job opportunities. However, a major issue for the local cultivation facility at Kubang Badak, Langkawi, is the underutilisation of the area in the ponds set aside for the cultivation of Caulerpa seaweed. This inefficiency results in lost opportunities to maximise Caulerpa production in the area and restricts the overall production capacity. This study therefore evaluated frond density, frond length, plate weight, daily growth rate and biomass yield over four weeks under white LED, pink LED and natural sunlight. Its practical significance lies in providing preliminary, site-specific evidence to guide the further development of multilevel Laktud cultivation in Langkawi. The novelty lies in assessing three lighting conditions within a multilevel arrangement at a local cultivation facility and reporting plate-level growth responses that reveal both promising LED performance and the variability associated with natural sunlight. Rueangnoi et al. (2025) reported that changing light intensities significantly affected the growth of sea grapes (*Caulerpa lentillifera*).

MATERIALS AND METHOD

The study was conducted in a controlled growth environment to assess the growth of Caulerpa lentillifera (Laktud) under different illumination conditions. Cultivation of Laktud was carried out for four weeks using nine plates (Figure 1) in a three-tiered cultivation system (Figure 2). Three plates were used for each illumination condition: white LED (W1, W2, W3), pink LED (P1, P2, P3) and natural sunlight (S1, S2, S3). No LED lights to allow development assessment under natural sunlight exposure.

Light intensity taken from the HOBO sensor data logger indicated light availability among cultivation sites. The highest position (S1) was 11022.3 lux in natural sunlight, while S2 and S3 were 376.7 and 150.7 lux. However, the cultivation levels with LEDs had the

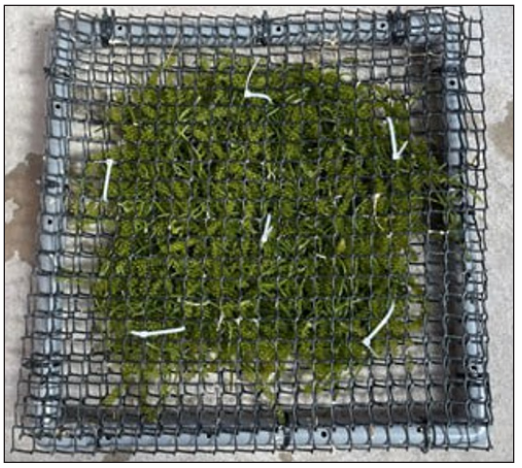

Figure 1. Plate used to cultivate Laktud



Figure 2. Multilevel cultivation with LED approach

same measured brightness. This difference is essential to the study's purpose, as natural sunlight provided more favourable illumination at the uppermost location but much reduced illumination at the lower levels. Thus, consistent LED brightness could be a practical way to improve the utilisation of vertical cultivation space. Nevertheless, the measured values in lux do not convert directly to photosynthetic photon flux density (PPFD) and so do not establish the photosynthetic light accessible to Laktud.

The data collected include biomass production, frond density, and the daily growth rate of frond length. Frond length and density were measured using a 100 cm^2 frame (Azcárate-García, 2022). The cultivation period is fixed at 4 weeks. DGR was computed as $[\ln(W_f) - \ln(W_i)]/t$ (day^{-1}), where W_i is the initial fresh weight, W_f is the final fresh weight, and t is the number of days in culture. Biomass yield was calculated as the final biomass per unit area of culture and length of cultivation (g m^{-2} day^{-1}). Fertilisation is done every two weeks (Islam et al., 2021), and a water-testing kit is used to check water quality. The optimum salinity levels should be in the range of 30 to 32 parts per thousand (ppt) and not less than 25 ppt (Fakhrulddin et al., 2021). Every two weeks, 80% of the pond's water is replaced with fresh seawater to maintain the optimum aquatic conditions.

Statistical evaluation was done to study the effectiveness of Laktud growth when exposed to light, whether it is pink LED, white LED or natural sunlight. The effects of light conditions and cultivation weeks on frond density and length were analysed by two-way analysis of variance (ANOVA). The daily growth rate (DGR) and biomass output under different illumination conditions were analysed by one-way ANOVA. The null hypothesis (H0) assumed that there were no significant variations in the evaluated growth parameters between the illumination treatments and, when relevant, the cultivation weeks. Statistical significance was defined as a P-value < 0.05.

RESULTS AND DISCUSSION

Results for frond density and frond length provide significant and important information about the overall productivity and quality of the cultivated *Caulerpa lentillifera* (Stuthmann et al., 2023). Figure 3 shows the graph of average frond density for four weeks of the cultivation period. The mean frond density for white LED light (W1, W2, W3) was the highest compared to pink LED light and natural sunlight. By week 4 (Table 1), plate W2 achieved the highest density, which was 79.33 cm2, compared to 78.67 cm^2 for pink LED light. However, natural sunlight showed a decline, with S3 at 3.67 cm^2 by week 4. This decrease may be a result of the inconsistency of natural sunlight compared to LED lighting.

Table 1
Value of density of fronds in four weeks (number per 100cm^2)

Plate	Density (cm^2)			
	Week 1	Week 2	Week 3	Week 4
P1	40.33	53.00	62.67	78.67
P2	56.33	62.67	63.33	71.00
P3	48.00	61.67	67.00	76.00
W1	45.33	58.33	64.67	70.00
W2	49.67	50.67	68.33	79.33
W3	52.00	54.33	64.67	73.67
S1	39.00	43.00	68.33	78.00
S2	13.67	18.00	13.33	9.67
S3	8.33	11.33	6.67	3.67

Table 2
Value of length of frond in four weeks

Plate	Length (cm)			
	Week 1	Week 2	Week 3	Week 4
P1	1.880	1.944	2.236	2.500
P2	1.592	2.139	2.361	2.678
P3	1.708	3.014	3.194	3.481
W1	1.667	2.139	2.694	2.922
W2	1.903	2.931	3.081	3.139
W3	2.556	3.093	3.925	4.017
S1	3.583	4.444	4.597	4.628
S2	1.700	2.125	1.955	1.886
S3	2.460	2.250	1.738	0.955

Two-way ANOVA showed significant differences in frond density between the different illumination treatments ($p<0.001$) and weeks of culture ($p = 0.004$). The frond density increased over the 4 weeks of cultivation and was higher under pink and white LED lights than under natural sunlight. This can be caused by the high demand for LED lighting to maintain constant light, where higher light intensity increases the energy available to algae for photosynthesis, leading to faster growth and possibly more ramuli (Apriliyanti et al., 2024). In the multi-level cultivation system, shading by natural sunlight can be avoided during growth.

Individual frond length at plate level was highest in S1 (4.628 cm) at Week 4, followed by W3 (4.017 cm) as shown in Figure 4. The higher frond lengths measured at S1 are probably attributable to its location at the highest point of the pond, where natural light was more favorable. The LED lighting configuration ensured uniform light intensity across all LED-illuminated cultivation levels. The lowest layers (S2 and S3) under natural sunlight had much reduced frond lengths, 1.886 cm and 0.955 cm, respectively as shown in Table 2. The results indicate a possible disadvantage of relying solely on natural sunlight

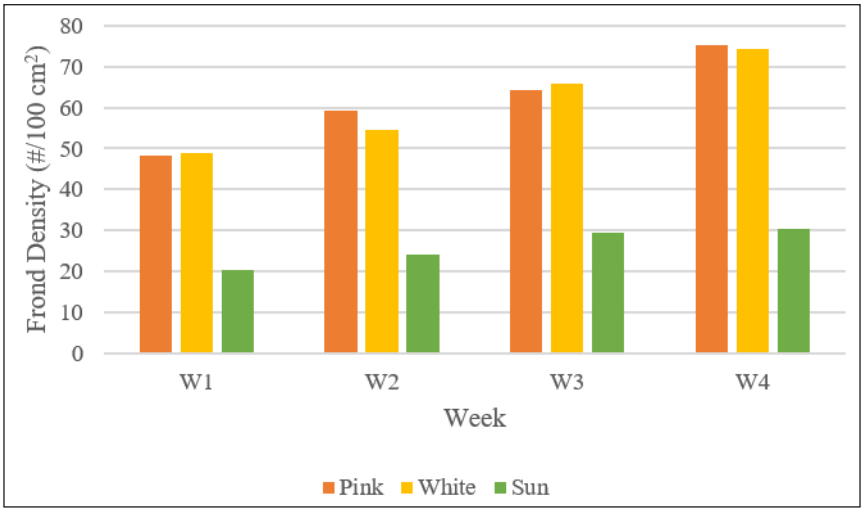

Figure 3. Average density of fronds in four weeks

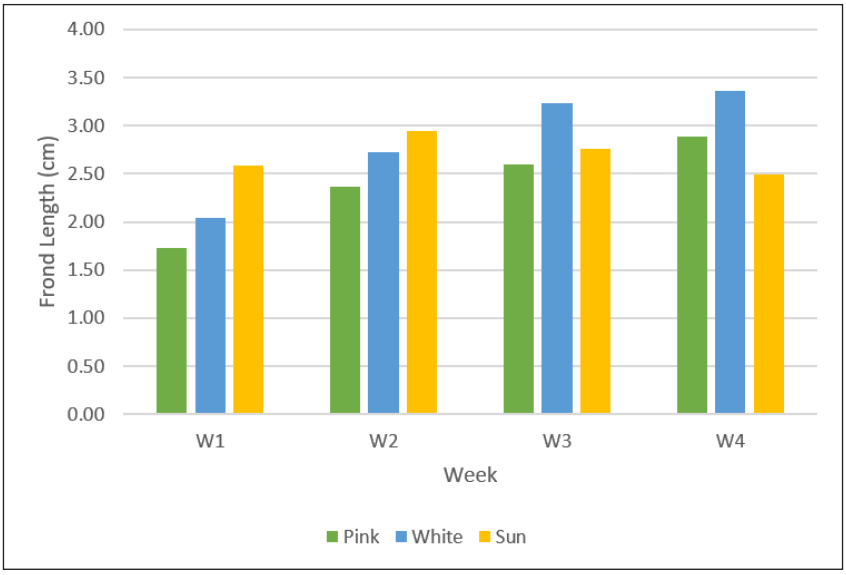

Figure 4. Average frond length over four weeks

in multilevel production systems, where ideal lighting conditions may be concentrated at the uppermost level.

Thus, the effect of LED illumination was examined as a potential means to improve lighting uniformity between culture tiers and to increase the efficiency of the available pond space for production. A broader spectrum from white LEDs may better suit Laktud's growth requirements, perhaps stimulating not only photosynthesis but also other physiological processes essential for elongation (Kim et al., 2023). This is supported by Alrajhi et al. (2023),

who found that the light spectrum significantly influenced many plant properties. However, the results should be considered as discrete observations at the plate level and not the treatment means, and further investigation is required to understand the impacts of lighting conditions and culture placement on growth performance.

However, according to the two-way ANOVA, it shows that there is no significant difference in frond length between light exposure ($p = 0.260$) and cultivation weeks ($p = 0.099$). However, the trends show that the LED light had the longest length in week 4, and the natural sunlight decreased in week 2.

The weight graph in Figure 5 illustrates the growth pattern for Laktud under all light conditions. At Week 4, the maximum weight reached was 1305 g for W2. Meanwhile, pink LED light indicated positive but slightly lower growth, with P3 reaching 1200 gram. However, natural sunlight showed inconsistent trends: S1 achieved a result similar to that under pink LED light, whereas S2 and S3 declined in weight. This underscores that Laktud received non-uniform light distribution under natural sunlight cultivation.

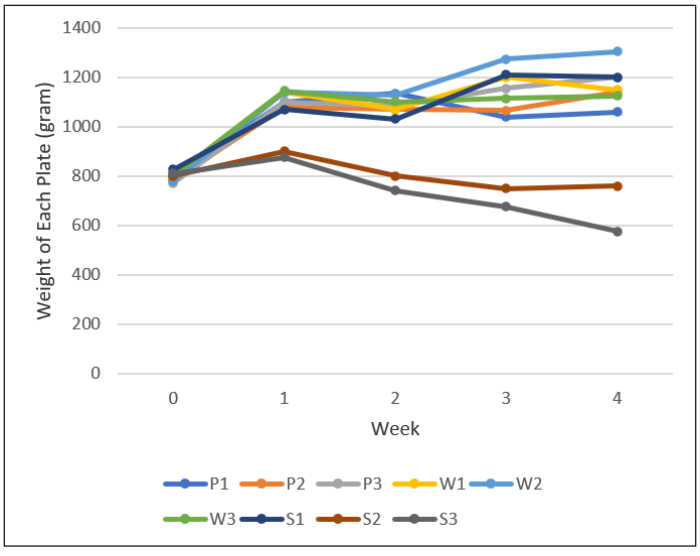

Figure 5. Weight of each plate in four weeks

White LED plates performed well, with W2 recording the highest biomass yield of 247.76 g m^{-2} day^{-1} among all plates (Figure 7). The daily growth rate (DGR) was also higher in LED-treated plates, with W2 having the highest DGR of 0.018551 day^{-1} as shown in Figure 6. These findings indicate that controlled, consistent LED lighting, particularly full-spectrum light, is significantly better for *Caulerpa lentillifera* biomass development than variable natural sunlight (Yang et al., 2022).

The one-way ANOVA showed no statistically significant differences in DGR ($p = 0.108$) or biomass yield ($p = 0.117$) between the lighting treatments. The white LED

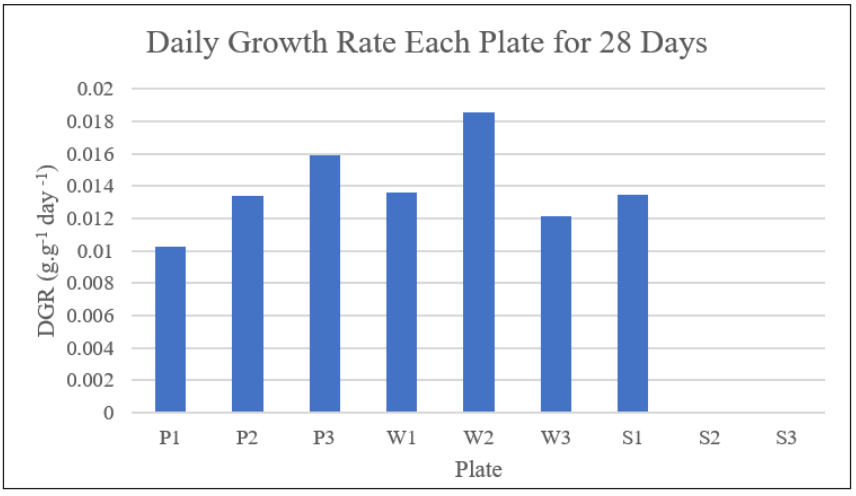

Figure 6. Daily growth rate for each cultivation plate (day^{-1})

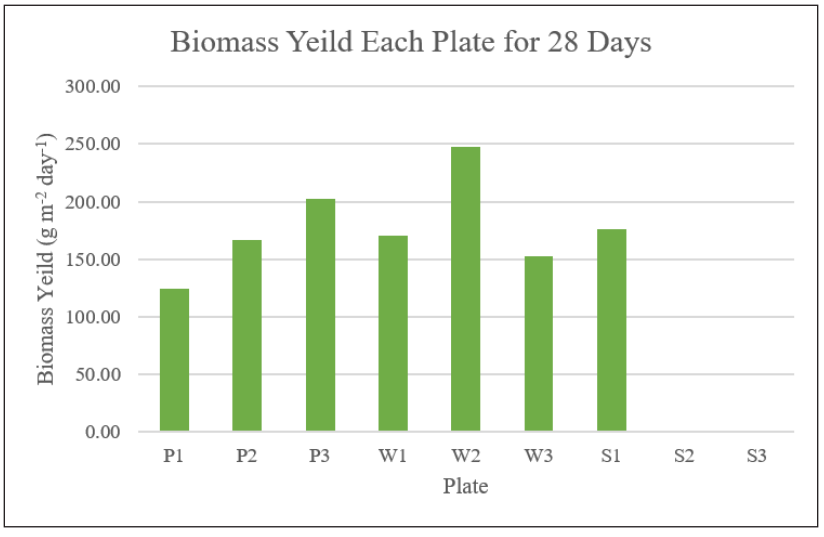

Figure 7. Biomass yield for each cultivation plate ($g\ m^{-2}\ day^{-1}$)

showed the highest mean values of both parameters, indicating its ability to induce growth and biomass yield. However, a larger sample size is needed to more accurately assess the effects of different lighting treatments on the growth performance of *Caulerpa lentillifera.*

The findings of this study underscore the potential benefits of multilevel cultivation using LED lighting for the cultivation of *Caulerpa lentillifera*. Controlled and consistent light distribution resulting from LED light offers a sustainable alternative to traditional sun-reliant cultivation and supports higher growth rate and biomass yield. Consequently, this innovation can enhance the productivity of *Caulerpa lentillifera*, which cannot meet

demand due to stock shortages resulting from overharvesting and unpredictable weather (Qudus et al., 2020).

CONCLUSION

In conclusion, multilevel cultivation with LED lighting is a feasible approach to increase the light distribution and support the growth of Laktud under land-based cultivation conditions in Kubang Badak, Langkawi. The LED lighting provides a more even distribution of light throughout the production system, unlike natural sunlight, which is affected by shade at the lower levels of cultivation. The results highlight the need for suitable lighting conditions for seaweed growth and the potential for multi-level cultivation. However, this study concentrated mainly on lighting conditions and growth performance, and the economic viability, long-term sustainability and socio-economic benefits of this cultivation technique were not directly addressed. Future studies should address the impact of different light intensities and cultivation conditions, energy consumption, production costs and economic feasibility to evaluate the feasibility of multilevel LED cultivation for sustainable seaweed production and its contribution to the development of coastal communities. This contributes to achieving the 17 United Nations Sustainable Development Goals (SDGs).

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