

Original Research Paper

Effects of Light Spectrum Variation on Biomass Development of *Caulerpa lentillifera*

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Abstract

Light spectrum plays a crucial role in photosynthesis and biomass development of marine macroalgae. This study aimed to evaluate the effects of different light spectra on biomass development of *Caulerpa lentillifera* in controlled cultivation systems. Four LED light treatments (white, red, yellow, and green spectra at 3000 lux intensity) were applied using a completely randomized design with three replications over 30 days. Growth parameters including absolute growth, relative growth, specific growth rate (SGR), and biomass residue were measured at 10-day intervals. Results showed that red light produced the highest absolute growth (0.107 ± 0.004 mg), relative growth ($2.39 \pm 0.15\%$), and SGR ($0.237 \pm 0.015\%$ day⁻¹), followed by white light (0.101 ± 0.015 mg, $2.26 \pm 0.34\%$, $0.224 \pm 0.034\%$ day⁻¹). All treatments exhibited biphasic growth patterns with peak biomass on day 10, followed by progressive decline. White light maintained the highest biomass residue ($64.4 \pm 23.3\%$), while green light showed the lowest performance across all parameters ($39.3 \pm 3.7\%$). The superior growth under red light is attributed to optimal absorption by photosystem II at 680 nm wavelength. This study recommends red light for maximizing short-term biomass production and white light for maintaining long-term stability in *C. lentillifera* cultivation systems.

Keywords: Biomass growth; *Caulerpa lentillifera*; Light spectrum; Macroalgae

INTRODUCTION

Seaweed represents a strategic fisheries commodity with high economic value and has become an important livelihood for coastal communities in Indonesia. *Caulerpa lentillifera*, commonly known as "sea grapes" or "green caviar", is a high-value macroalgal species belonging to the class Chlorophyceae that is extensively cultivated throughout the Indo-Pacific region (Chen et al., 2019). This species is rich in protein, vitamins, essential minerals, and bioactive compounds with potential applications in the food, pharmaceutical, and cosmetic industries (Chen et al., 2019; Antara et al., 2022; Nurkolis et al., 2023; Stuthmann et al., 2023). *Caulerpa lentillifera* exhibits a palatable flavor profile, making it suitable for consumption and the development into high-quality seafood condiments (Zhou et al., 2025). With a coastline spanning 108,000 km and potential mariculture areas covering 12.12 million km² (BPS, 2024), Indonesia possesses substantial potential for large-scale development of *C. lentillifera* cultivation to support sustainable marine economy.

The growth and productivity of seaweed are significantly influenced by aquatic environmental conditions, particularly light as the primary energy source for photosynthesis. Light intensity and spectral quality play crucial roles in algal metabolism, morphogenesis, and biomass accumulation through the activation of photosynthetic pigments such as chlorophyll-a, chlorophyll-b, and carotenoids, which absorb specific wavelengths (Mulders et

al., 2014; Bonomi Barufi et al., 2015; Wu, 2016; Pagels et al., 2020; Maltsev et al., 2021). Chlorophyll a is the primary pigment responsible for sunlight energy capture, while other chlorophylls and carotenoids are accessory pigments that assist in transporting the absorbed energy (Glemser et al., 2016; Cikoš et al., 2022). Research has demonstrated that optimal growth of *Caulerpa* sp. occurs under high light intensity ($120 \mu\text{mol photons m}^{-2}\text{s}^{-1}$), which stimulates thallus regeneration and cell differentiation (Ukabi et al., 2013; Charrier et al., 2017). Interactive effects of light and temperature have been studied, showing that temperature effects on photosynthesis and respiration of *C. lentillifera* can be reversed by increases in nitrate level (Guo et al., 2015b; Terada et al., 2021; Cai et al., 2021; Stuthmann et al., 2023). Controlled cultivation systems utilizing Light Emitting Diode (LED)-based artificial lighting technology enable spectral manipulation to optimize photosynthetic efficiency and biomass productivity (Huang et al., 2021; Kim et al., 2015; Kang et al., 2020).

Despite possessing abundant macroalgal biodiversity, *C. lentillifera* cultivation in Indonesia continues to face challenges of low productivity and harvest instability due to fluctuations in natural environmental conditions, including seasonal variations, water quality, and light intensity (Yuliyana et al., 2022). The primary challenge in *C. lentillifera* cultivation lies in its dependence on natural conditions and limited environmental factor control (Eviana et al., 2024). The

primary limiting factors include inadequate appropriate cultivation technology, limited knowledge of optimal culture parameters, and the absence of standardized cultivation protocols (Ismail et al., 2024). Controlled cultivation systems in closed systems such as water tanks allow real-time monitoring and effective regulation of seaweed culture conditions including nutrients, light, pH value, CO₂ and salinity to produce more target products (Zhang et al., 2022). Specific research on the effects of light spectrum on *C. lentillifera* growth in controlled systems remains extremely limited. White LED light has been shown to be the optimal supplementary light when cultivating macroalgae because it promotes seaweed growth while maintaining protein production (Huang et al., 2021). Different wavelengths of light and water turbulence have interactive effects on the growth of green macroalgae, with blue light cultures showing enhanced growth irrespective of photosynthetic performance (Lee et al., 2024). Controlled cultivation approaches utilizing LED technology with modulated light spectra offer a solution to overcome these limitations by creating consistent optimal environmental conditions throughout the year (Schmid et al., 2023; Pure Algae, 2024).

This study aims to investigate the effects of light spectral variations on the biomass development of *C. lentillifera* in a controlled cultivation system to identify the optimal light spectrum that supports maximum growth. The research findings are expected to provide significant contributions to the development of more efficient and productive seaweed cultivation protocols, ensure continuous production of high-quality yields year-round, and enhance the competitiveness of the *C. lentillifera* cultivation industry in Indonesia. Automation and optimization of seaweed aquaculture systems through development of cultivation techniques can make the process more efficient and cost-effective (Schmid et al., 2023). These findings will support the development of modern aquaculture technology based on controlled lighting that can be widely applied by seaweed farmers to improve productivity and the sustainability of the national marine economy.

RESEARCH METHODS

Study Period and Location

This study was conducted from September to October 2024 in the coastal waters of Batu Layar, Senggigi, West Lombok, West Nusa Tenggara, Indonesia, where *Caulerpa lentillifera* samples were collected. Experimental cultivation was carried out at the Production and Reproduction Laboratory, Faculty of Agriculture, University of Mataram.

Experimental Design

This laboratory-based experimental study employed a Completely Randomized Design (CRD) with four light spectrum treatments and three replicates, yielding 12 experimental units. The treatments tested included: (A) white light as control, (B) red light, (C) yellow light, and (D) green light, all maintained at a constant light intensity of 3000 lux. Randomization of experimental units was performed using a lot drawing method to ensure objective treatment distribution.

Population and Research Samples

The research population consisted of *Caulerpa lentillifera* naturally growing in the waters of Batu Layar,

Senggigi, West Lombok, characterized by fresh green thalli, absence of bleaching, and intact ramulus structures. A total of 144 grams of samples was divided into 12 experimental units, with each unit containing 12 grams wet weight. The sampling technique employed purposive sampling based on criteria of healthy morphology and uniform thallus size (Estrada et al., 2020)

Research variables included independent variables consisting of light spectra (white, red, yellow, green) and dependent variables comprising absolute growth, relative growth, specific growth rate, and biomass residue. Data collection was performed through biomass weighing using a digital balance (precision 0.001 g) at 10-day intervals throughout the cultivation period.

Research materials consisted of fresh *C. lentillifera*, filtered and settled natural seawater (24 hours), and fertilizers including Urea (46% N), TSP (47% P₂O₅), and NPK (15-9-20) as macronutrient sources with concentrations of 30 ppm nitrogen, 4 ppm phosphorus, and 6 ppm potassium. Research equipment included 3-liter glass jars (12 units), spectrum-specific LED lamps, aeration system (blower, tubing, diffuser), digital balance, luxmeter, thermometer, refractometer, and digital pH meter.

Experimental Procedures

The experimental procedure commenced with preparation of cultivation containers consisting of glass jars cleaned with detergent, rinsed with freshwater, and air-dried for 24 hours. Each container was filled with 1.5 liters of seawater that had been filtered using cotton filters and settled for 24 hours, then enriched with macronutrient addition according to predetermined concentrations. *C. lentillifera* seedlings selected based on healthy morphological criteria were acclimatized under laboratory temperature conditions for 24 hours, then stocked into cultivation containers at an initial weight of 12 grams per container in the morning to minimize thermal stress. An aeration system was installed in each container at moderate intensity to ensure optimal water circulation and gas exchange. LED lighting systems with light spectra corresponding to treatments were mounted above the cultivation containers and calibrated to 3000 lux intensity using a luxmeter.

Maintenance operations included complete water changes (1.5 liters per container) every 10 days and periodic removal of dead or degraded biomass. Water quality parameters (temperature, salinity, pH) were measured every 10 days at four different times (morning, midday, afternoon, night) using a thermometer (precision 1°C), refractometer (precision 1 ppt), and digital pH meter (precision 0.01 units). Biomass weighing was conducted every 10 days using a digital balance to calculate growth parameters until the end of the cultivation period.

Data Analysis

Growth data were analyzed using four main parameters following Hasanah et al. (2025). Absolute growth (Abs) was calculated using the formula $Abs = W_t - W_0$, where W_t represents final weight (g) and W_0 represents initial weight (g). Relative growth (GR) was calculated using the formula $GR = [(W_t - W_0)/W_0] \times 100\%$, representing the percentage weight increase during the cultivation period. Specific growth rate (SGR) was calculated using the formula: $SGR =$

$[(W_t/W_0)^{(1/t)} - 1] \times 100\%$, where t represents cultivation time (days), indicating the percentage of daily growth. Biomass residue (RB) was calculated using the formula $RB = (W_a/W_p) \times 100\%$, where W_a represents final experimental weight (g) and W_p represents weight at peak growth (g), describing the percentage of biomass retained from peak biomass.

The obtained data were analyzed using one-way analysis of variance (ANOVA) to determine the effect of light spectrum treatments on *C. lentillifera* growth parameters at a 95% confidence level. When significant differences were detected ($p < 0.05$), post-hoc analysis was performed using the Least Significant Difference (LSD) test to determine the optimal treatment using statistical software.

RESULTS AND DISCUSSION

Water Quality Parameters

Water quality parameters remained relatively stable throughout the 30-day cultivation period and within optimal ranges for *C. lentillifera* growth. Salinity ranged from 33-35 ppt, pH from 7.8-8.1, and temperature from 28-30°C. These values were consistent with optimal conditions reported for *Caulerpa* species cultivation (Guo et al., 2015a, 2015b), indicating that the controlled cultivation system successfully maintained suitable environmental conditions throughout the experimental period.

The stability of water quality parameters across all treatments ensures that observed differences in growth performance can be attributed primarily to light spectrum treatments rather than environmental variations. This controlled condition is essential for accurately evaluating the specific effects of different light spectra on *C. lentillifera* biomass production.

Biomass Growth Pattern of *Caulerpa lentillifera*

Observation of *C. lentillifera* biomass over 30 days revealed a consistent biphasic growth pattern across all light spectrum treatments. The first phase (day 0 to day 10) was characterized by biomass increase in all treatments, while the second phase (day 10 to day 30) exhibited progressive biomass decline (Figure 1). Maximum biomass was achieved on day 10, with the highest value obtained under green light treatment (4.66±0.18 g), followed by white light (4.61±0.20 g), red light (4.59±0.14 g), and yellow light (4.52±0.05 g).

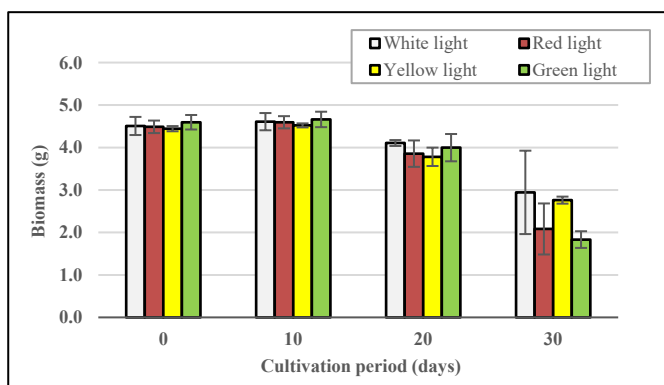


Figure 1. Biphasic biomass growth pattern of *C. lentillifera* under different light spectra over 30 days.

The observed biphasic pattern indicates two distinct physiological phases in *C. lentillifera* response to controlled

cultivation conditions. The first phase represents an acclimatization and active growth period where algal cells adapt to new environmental conditions and utilize internal energy reserves for initial growth. Water quality parameters remained stable and within optimal ranges throughout this period, suggesting that the observed growth patterns were primarily influenced by light spectrum treatments rather than environmental fluctuations. Research by Ghedifa et al. (2021) on *Ulva lactuca* demonstrated a similar pattern where optimal growth occurred during the early cultivation phase before declining due to secondary metabolite accumulation and nutrient limitation. The second phase, characterized by biomass decline, is likely caused by nutrient depletion in the medium, allelopathic compound accumulation, or physiological stress due to microenvironmental changes within the closed cultivation containers.

The biomass decline after reaching peak growth indicates limitations in the controlled cultivation system employed. Marques et al. (2021) reported that macroalgal biomass decline in closed systems is often associated with toxic metabolic product accumulation and gradual water quality deterioration. The implications of these findings emphasize the need for optimization of media replacement protocols and periodic nutrient supplementation to maintain sustainable growth of *C. lentillifera*. The results also demonstrate that the optimal cultivation period for *C. lentillifera* in controlled systems is 10 days, when biomass reaches maximum value before degradation occurs.

Absolute Growth of *Caulerpa lentillifera*

Absolute growth of *C. lentillifera* cultured for 10 days showed variation among light spectrum treatments, ranging from 66-107 mg (Figure 2). Red light treatment produced the highest absolute growth (0.107±0.004 mg), followed by white light (0.101±0.015 mg), yellow light (0.078±0.008 mg), and green light (0.066±0.005 mg). Statistical analysis revealed that different light spectra had a significant effect ($p > 0.05$) on the absolute growth of *C. lentillifera*. The superiority of red light in supporting absolute growth of *C. lentillifera* can be explained through the absorption efficiency of photosynthetic pigments at red wavelengths (660-700 nm). Chlorophyll-a as the primary photosynthetic pigment has absorption peaks in the red spectrum around 680 nm, enabling red light to be optimally absorbed by photosystem II to generate ATP and NADPH required for carbon fixation and biomass biosynthesis (Blankenship, 2008; Kang et al., 2020). Research by Ghedifa et al. (2021) on *Ulva lactuca* and Marques et al. (2021) on various green algae species also reported that red light consistently produced the highest biomass growth compared to other light spectra. LSD test results indicated that absolute growth under white light was not significantly different from red light but differed significantly from yellow and green light, suggesting that the red spectrum component in white light contributes significantly to growth.

The low absolute growth under green light treatment (0.066 mg) aligns with the principle that green light (495-570 nm) is largely reflected by chlorophyll and therefore cannot be efficiently utilized for photosynthesis. Nishio (2000) explained that the absorption coefficient of green light by chlorophyll is considerably lower compared to red and blue light, resulting in limited energy available for photochemical processes. However, studies by Liu & van Iersel (2021) and

Terashima et al. (2009) demonstrated that at high light intensities, green light can contribute to photosynthesis through deeper tissue penetration. The discrepancy between this research and those findings is likely due to differences in light intensity used (3000 lux) and the relatively thin morphological characteristics of *C. lentillifera* thallus, rendering the penetration advantage of green light less significant. The implications of these findings are that the use of red light or spectral combinations with high red components is highly recommended for optimizing *C. lentillifera* biomass production in controlled cultivation systems.

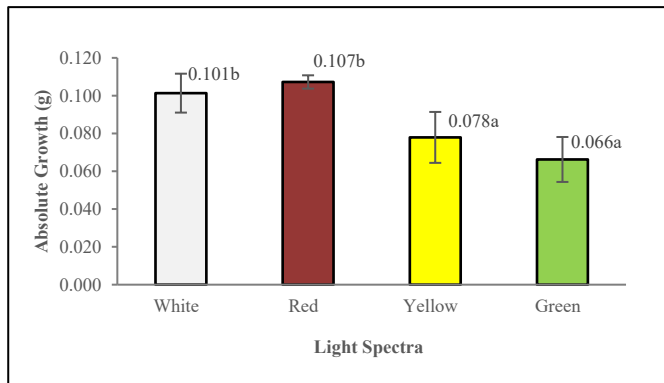


Figure 2. Absolute growth of *C. lentillifera* under different light spectra. Error bars represent standard deviation; different letters indicate significant differences ($p < 0.05$).

Relative Growth of *Caulerpa lentillifera*

Relative growth of *C. lentillifera* during 10 days of cultivation ranged from 1.44-2.39%, showing a pattern consistent with absolute growth parameters (Figure 3). Red light produced the highest relative growth (2.39±0.15%), followed by white light (2.26±0.34%), yellow light (1.76±0.33%), and green light (1.44±0.21%). Statistical analysis revealed that different light spectra had a significant effect ($p < 0.05$) on the relative growth of *C. lentillifera*.

The consistency of relative growth results with absolute growth reinforces the conclusion that red light is the optimal spectrum for *C. lentillifera* growth. The higher relative growth percentage under red light (2.39%) compared to green light (1.44%) demonstrates that light energy conversion efficiency into biomass differs significantly among light spectra. Optimal activation of photosystem II by red light enhances photosynthetic electron flow and more efficient ATP synthesis, thereby increasing carbon fixation rates and biomass biosynthesis (Kang et al., 2020). Research by Marques et al. (2021) on *Gracilaria* sp. reported similar results where the highest relative growth was obtained under red light treatment with a 40% increase compared to white light. The difference in growth percentages between this study and Marques et al. (2021) is likely due to differences in algal species, light intensity, and applied culture conditions.

White light exhibited relative growth not significantly different from red light ($p > 0.05$) because it contains a complete spectrum including beneficial red light components for photosynthesis. The spectral balance in white light enables simultaneous activation of various photosynthetic pigments, including chlorophyll a, chlorophyll b, and carotenoids, thereby supporting comprehensive photosynthetic processes

(Blankenship, 2008; Massa et al., 2008). This explains why white light can produce growth nearly equivalent to red light despite slightly lower energy efficiency. The practical implication of this finding is that both red and white light can be used as lighting sources in commercial *C. lentillifera* cultivation, with consideration that white light is more readily available and cost-effective compared to monochromatic red LEDs.

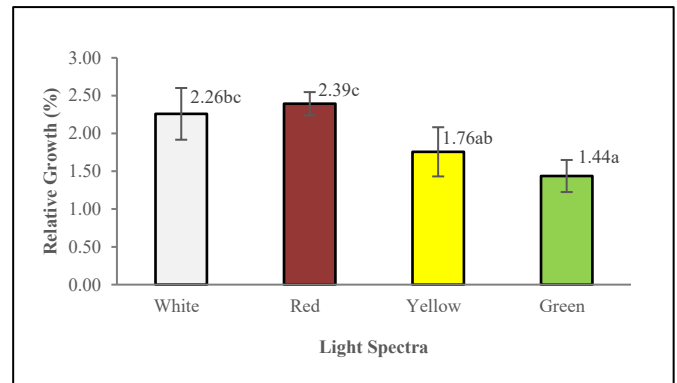


Figure 3. Relative growth of *C. lentillifera* under different light spectra. Error bars represent standard deviation; different letters indicate significant differences ($p < 0.05$).

Specific Growth Rate of *Caulerpa lentillifera*

The specific growth rate (SGR) of *C. lentillifera* cultured for 10 days ranged from 0.143-0.237% per day, showing a pattern similar to previous growth parameters (Figure 4). Red light produced the highest SGR (0.237±0.015% per day), followed by white light (0.224±0.034% per day), yellow light (0.174±0.032% per day), and green light (0.143±0.021% per day). Statistical analysis revealed that different light spectra had a significant effect ($p < 0.05$) on the SGR of *C. lentillifera*.

Specific growth rate is an important indicator for evaluating the daily growth efficiency of organisms in cultivation systems. The highest SGR value under red light (0.237% per day) indicates that this spectrum produces the most efficient daily biomass accumulation rate. The underlying molecular mechanism relates to optimal red light absorption by photosystem II, which has chlorophyll-a absorption peaks around 680 nm, enabling efficient energy transfer for primary photochemical processes in photosynthesis (Blankenship, 2008). Research by Ghedifa et al. (2021) reported SGR of *Ulva lactuca* under red light reaching 3.5% per day, considerably higher than this study. The difference in SGR values is likely due to species differences, culture conditions (closed vs. open systems), and environmental parameters such as temperature and salinity that affect algal metabolic rates.

LSD test results indicated that SGR under red light was not significantly different from white light ($p > 0.05$), but differed significantly from yellow and green light, confirming the consistency of *C. lentillifera* growth response to light spectra. The low SGR under green light (0.143% per day) indicates energy limitation due to suboptimal photosynthesis, which can result in physiological stress and reduced daily growth rates. Brodersen et al. (2008) explained that although green light has deeper penetration capability, in organisms

with thin thallus structures like *C. lentillifera*, this advantage becomes irrelevant because entire tissues are already uniformly exposed to light. The implication of this finding is that to achieve maximum productivity in *C. lentillifera* cultivation, the use of red or white light at optimal intensity (3000 lux) is highly recommended, with an estimated optimal harvest time on day 10 to maximize biomass yield.

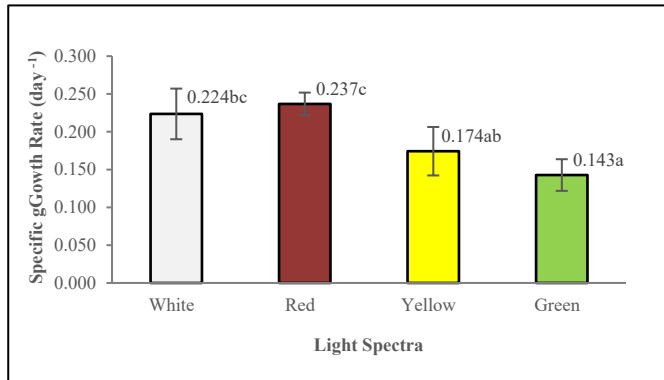


Figure 4. Specific growth rate of *C. lentillifera* under different light spectra. Error bars represent standard deviation; different letters indicate significant differences ($p < 0.05$).

Biomass Residue of Caulerpa lentillifera

Biomass residue of *C. lentillifera* cultured for 30 days ranged from 39.3-64.4%, showing a different pattern from previous growth parameters. White light produced the highest biomass residue (64.4±23.3%), followed by yellow light (61.1±1.3%), red light (45.6±14.0%), and green light (39.3±3.7%). Statistical analysis revealed that different light spectra had a significant effect ($p < 0.05$) on biomass residue, although LSD test results showed white light was not significantly different from all other treatments.

An interesting phenomenon observed was that although red light produced the best growth, its biomass residue was relatively low (45.6%), indicating a trade-off between growth rate and long-term biomass stability. Red light that intensively activates photosynthesis may also increase reactive oxygen species (ROS) production, which can cause oxidative stress and cellular degradation (Wang et al., 2023). Hogewoning et al. (2010) reported that exposure to high-intensity red light can cause photoinhibition and ROS accumulation that damages cellular components such as lipid membranes and proteins. The high biomass residue under white light (64.4%) indicates that balanced spectra provide better physiological stability through synthesis of pigments and secondary metabolites important for cellular resistance to oxidative stress (Mitchell et al., 2012).

Yellow light exhibited high biomass residue (61.1%) despite suboptimal growth, indicating that this spectrum provides more stable conditions for long-term biomass maintenance. This is likely related to the absence of excessive photoinhibition in the yellow spectrum compared to red light, which can trigger photosynthetic stress (Hogewoning et al., 2010). The low biomass residue under green light (39.3%) demonstrates the highest degradation level, consistent with low photosynthetic efficiency and limited energy to maintain biomass integrity over the long term. The practical implications of these findings are that for short-term

production (10 days), red or white light is optimal for yield maximization, but for long-term cultivation (30 days), white or yellow light is more recommended to maintain biomass stability and quality. Further research is needed to optimize light spectrum combinations and intensities that can produce high growth while maintaining biomass stability in commercial cultivation systems.

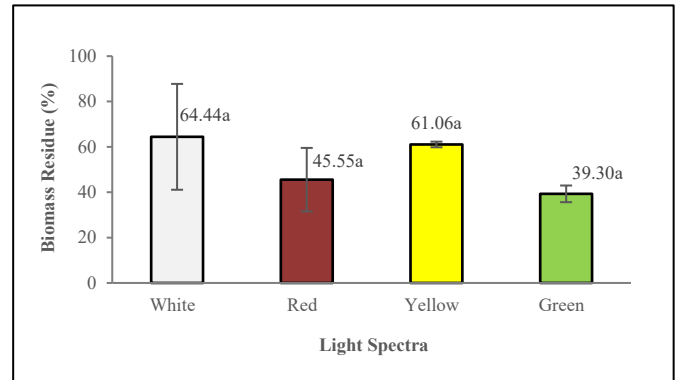


Figure 5. Biomass residue of *C. lentillifera* after 30 days under different light spectra. Error bars represent standard deviation; different letters indicate significant differences ($p < 0.05$).

CONCLUSION

Red light spectrum produced optimal growth of *Caulerpa lentillifera* with the highest absolute growth (0.107±0.004 mg), relative growth (2.39±0.15%), and specific growth rate (0.237±0.015% per day) compared to white, yellow, and green light spectra. All light spectrum treatments exhibited a biphasic growth pattern with biomass increase during the initial phase (day 0 to day 10) followed by progressive decline in the final phase (day 10 to day 30). White light spectrum provided the best long-term biomass stability with the highest biomass residue (64.4±23.3%), while green light spectrum produced the lowest biomass residue (39.3±3.7%). This study recommends the use of red or white light as the optimal lighting source for *C. lentillifera* cultivation in controlled systems with an optimal harvest period of 10 days to maximize biomass productivity.

Cultivators of *C. lentillifera* are recommended to use red spectrum LED lamps during the early cultivation period (first 10 days) to maximize growth rate and biomass accumulation. Application of white light can be considered for long-term cultivation (more than 10 days) to maintain biomass stability and quality. Further research is needed to investigate the effects of combined light spectra (red-blue or red-white) on growth and bioactive compound content of *C. lentillifera*. Optimization of specific light intensities for each color spectrum and analysis of nutritional profiles and secondary metabolites from cultivation under various light treatments need to be evaluated to support the development of more efficient and productive commercial cultivation protocols.

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