Original Research Article

THE EFFECT OF WATER EXCHANGE INTERVALS ON THE GROWTH OF *Caulerpa lentillifera*

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ABSTRAct

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| This research aims to analyze the effect of water exchange intervals on the growth of *Caulerpa lentillifera* and determine the optimal water exchange interval for the growth of *Caulerpa lentillifera*. This research was conducted for 45 days, with maintenance activities carried out at the Production and Reproduction Laboratory, Faculty of Agriculture, University of Mataram. This research was conducted using a Completely Randomized Design (CRD) method. The method used in this research was experimental, employing 4 treatments and 3 replications with A (daily water exchange), B (water exchange every 5 days), C (water exchange every 10 days), and D (water exchange every 15 days). The seedlings used in this research were collected from the waters of Batu Layar, Senggigi, West Lombok. The seaweed required for this research totaled 120 g, with a distribution of 3 g per research container. This research utilized 12 glass jar units, each filled with 1 liter of seawater. This research also involved the addition of nutrients to support optimal growth of *Caulerpa lentillifera*. The culture medium was enriched with the addition of nitrogen (N) 30 ppm, phosphorus (P) 4 ppm, and potassium (K) 6 ppm. Based on the results of the Least Significant Difference (LSD) test, different water exchange intervals showed a significant effect *(p<0.05)* on the absolute growth of *Caulerpa lentillifera*. Based on the results of the Least Significant Difference (LSD) test, water exchange intervals showed a significant effect *(p<0.05)* on the relative growth of *Caulerpa lentillifera*. Based on the results of the Least Significant Difference (LSD) test, water exchange intervals showed a significant effect *(p<0.05)* on the specific growth rate of *Caulerpa lentillifera*. Based on the results of the Least Significant Difference test *(p<0.05)*, water exchange intervals showed a significant effect *(p<0.05)* on the biomass residue of *Caulerpa lentillifera*. In conclusion, the water exchange interval of treatment C (water exchange every 10 days) showed the best performance in almost all measured growth parameters, with a relative growth value of 13.42%, daily specific growth rate of 0.630% per day, biomass residue of 58.68%, and absolute growth of 504.0 mg. |

*Keywords: water exchange interval, caulerpa lentillifera, growth, water quality.*

1. INTRODUCTION

*Caulerpa lentillifera* is one of the green algae species from the family *Caulerpaceae* that has high economic value and great potential for development in aquaculture. This species is known by various local names such as "sea grapes", "green caviar", or "lato" in the Philippines, and "anggur laut" in Indonesia. In the context of cultivation, environmental factors such as water quality and water exchange play a crucial role in determining the growth rate and productivity of *Caulerpa lentillifera* (Hapsari et al., 2023).

Indonesia has great potential for the development of *Caulerpa lentillifera* cultivation given its supportive geographical conditions with extensive coastlines and suitable tropical aquatic ecosystems. The development of Caulerpa cultivation in Indonesia has experienced significant growth in the last decade, particularly in eastern Indonesia regions such as Maluku, Papua, and Nusa Tenggara. Several regions in Indonesia have developed commercial *Caulerpa lentillifera* cultivation, focusing on environmentally friendly and sustainable cultivation techniques. Maluku Province, particularly the Kei Islands, has become a major production center using traditional cultivation systems that have been modified with modern technology. Additionally, Bali and West Nusa Tenggara regions have also begun developing Caulerpa cultivation as a diversification of aquaculture products (Santoso et al., 2012).

This development is supported by increasing domestic and international market demand for seaweed products that have high nutritional value and health benefits. *Caulerpa lentillifera* is rich in protein, minerals, vitamins, and bioactive compounds that are beneficial for human health, making it a promising commodity for further development (Matanjun et al., 2009).

Water exchange is one of the important management practices in *Caulerpa lentillifera* cultivation that aims to maintain the quality of the cultivation environment and optimize algal growth. The water exchange process helps remove the accumulation of metabolic products, maintain nutritional balance, and increase dissolved oxygen levels in the cultivation medium (Caprio *et al.,* 2019).

The efficiency of water exchange in Caulerpa cultivation can be achieved through the implementation of a planned and controlled system. An efficient water exchange system not only considers the frequency of exchange, but also the volume of water exchanged, the quality of replacement water, and the optimal exchange timing. This approach allows for the maintenance of stable environmental conditions while minimizing water usage and operational costs (Zhang *et al.,* 2022).

Water exchange interval is one of the crucial water quality management aspects in intensive cultivation systems. Proper water exchange can maintain optimal conditions of water physicochemical parameters, remove harmful metabolites, and provide the necessary nutrients for growth. However, information regarding the optimal water exchange interval for *Caulerpa lentillifera* cultivation is still limited, thus further research is needed to optimize the cultivation techniques for this species.

2. RESEARCH METHODS

2.1 Time and Location

This research was conducted for 45 days from august 17 to september 30, 2024, with maintenance activities carried out at the production and reproduction laboratory, faculty of agriculture, university of mataram.

2.2 Research Method

this research used an experimental method by testing four water exchange interval treatments, where each treatment was replicated three times. The treatments applied included: treatment a (daily water exchange), treatment b (water exchange every five days), treatment c (water exchange every ten days), and treatment d (water exchange every fifteen days). The research design used a completely randomized design (crd) with a randomization method using a lottery system

**2.3 Research Preparation**

**2.3.1 Container Preparation**

The containers used in this research were glass jars with a volume of 3 liters, totaling 12 units. Each research container was filled with 1 liter of water. Before use, the jars were washed using detergent to remove dirt and kill bacteria attached to the glass surface, then rinsed with fresh water until clean. After the washing process was completed, the jars were drained at room temperature for one day or until completely dry.

**2.3.2 Medium Preparation**

The maintenance medium used in this research was seawater collected directly from the sea using jerry cans, then transferred into prepared storage tanks. Before being stored, the seawater was first filtered using a plastic funnel containing filter cotton, then settled for 1 day. After the settling process was completed, the culture medium was ready for use.

**2.3.3 Aeration Installation**

After the container preparation and seawater collection were completed, the next step was the installation of aeration systems. The aeration used totaled 12 units, with each container equipped with 1 unit of aeration.

**2.3.4 Seedling Preparation**

The seaweed used in this research was *Caulerpa lentillifera* collected from the waters of Batu Layar, Senggigi, West Lombok. The seaweed seedlings were wrapped using fish wrapping plastic, then transported using motorized vehicles. The seaweed required for this research was approximately 120 grams for 12 research containers, with a distribution of 3 grams per cultivation container. After the seaweed was collected, the seedlings were stored using containers in the laboratory and acclimated for one day at laboratory room temperature. The purpose of acclimation was to allow the seaweed to adapt to the new environmental temperature conditions where cultivation would be conducted.

**2.4 Research Stages**

**2.4.1 Water Medium Filling**

The previously prepared seawater was transferred into cultivation containers in the form of glass jars with a volume of 3 liters. This research used 12 glass jar units as cultivation containers. Each container was filled with 1 liter of seawater, resulting in a total water volume of 12 liters used in this research. Water filling was conducted carefully to avoid contamination and ensure optimal medium conditions for algal growth.

**2.4.2 Fertilizer Application**

Nutrient addition was conducted to support optimal growth of *Caulerpa lentillifera*. The culture medium was enriched with the addition of nitrogen (N) at a concentration of 30 ppm, phosphorus (P) at a concentration of 4 ppm, and potassium (K) at a concentration of 6 ppm. These nutrient concentrations refer to the method developed by Mukhlis *et al.* (2023). Nitrogen and phosphorus are macroelements that are very important for the growth and development of algal vegetative structures, while potassium plays a role in metabolic processes and cellular osmoregulation.

**2.4.3 Seedling Selection and Initial Weighing**

The *Caulerpa lentillifera* seedlings used in this research were superior and healthy seedlings with the following criteria: fresh green color, no bleaching, intact thallus structure, and free from epiphytes or other attached organisms. Each seedling was weighed with an initial weight of 3 grams using an analytical balance.

**2.4.4 Aeration System Installation**

Each cultivation container was equipped with one aeration point installed through a hole that had been made in the glass jar lid. This aeration system used an air pump with moderate intensity to ensure optimal oxygen circulation in the cultivation medium. Aeration functions to maintain dissolved oxygen content, prevent water stratification, and facilitate the gas exchange required for algal photosynthesis and respiration processes.

**2.4.5 Lighting System Setup**

An artificial lighting system was installed on the cultivation rack to provide consistent light intensity. The light intensity used during the cultivation period was 2000 lux, measured using a lux meter to ensure uniform lighting across all experimental units. This lighting setup is important because *Caulerpa lentillifera* is a photosynthetic organism that requires light for its metabolic processes and growth. The applied photoperiod followed a 12:12 hour light-dark cycle to mimic natural conditions.

**2.4.6 Water Quality Monitoring**

Water quality parameters were monitored regularly to ensure optimal cultivation environmental conditions. The parameters measured included temperature using a digital thermometer, salinity using a refractometer, and pH using a pH meter. Water quality measurements were conducted once a week at the same time to maintain data consistency. Water quality monitoring is crucial because changes in physicochemical parameters can affect the growth rate and physiological condition of *Caulerpa lentillifera*.

**2.4.7 Treatment Application**

Water exchange was conducted according to the predetermined time intervals based on the research treatments. The exchange was performed totally (100%) to maintain water quality and avoid metabolite accumulation that could inhibit growth. The water exchange process was carried out in the morning when the environmental temperature was still low to minimize thermal stress on the seedlings. The new seawater used had undergone temperature and salinity adjustment processes before being introduced into the cultivation containers.

**2.4.8 Growth Measurement and Seedling Condition Evaluation**

Wet weight measurement of samples was conducted every ten days using a digital balance with an accuracy of 0.001 grams. During the maintenance period, visual observations were made of physiological condition changes in *Caulerpa lentillifera*, including identification of tissues that experienced death or bleaching. Dead or degraded tissues were cut and removed from the cultivation containers to prevent contamination and water quality deterioration. The discarded parts were weighed separately for growth data analysis and mortality rate purposes. This evaluation process is important for monitoring seedling responses to the given treatments and identifying factors that can affect cultivation succes.

**2.5 Research Parameters**

**2.5.1 Research Parameters**

1. **Absolute Growth**

Absolute growth is the increase in weight and length of organisms during the maintenance period. This parameter indicates the difference between the final weight and initial weight of organisms expressed in grams. The measurement of absolute growth of *Caulerpa* sp. was calculated using the formula proposed by Effendie (1997) as follows:

**H = Wt - Wo**

Where:

* H = Absolute growth (g)
* Wt = Weight of *Caulerpa* sp. at the end of the research (g)
* Wo = Weight of *Caulerpa* sp. at the beginning of the research (g)
1. **Relative Growth**

Relative growth is the percentage increase in organism weight during the maintenance or cultivation period. This parameter describes the growth efficiency of organisms expressed as a percentage. The relative growth rate can be calculated using the formula proposed by Effendie (1997) as follows:

**X = (Wt - Wo)/Wo × 100%**

Where:

* X = Relative growth (%)
* Wt = Average final weight (g)
* Wo = Average initial weight (g)
1. **Specific Growth Rate**

Specific growth rate (SGR) is the percentage of daily growth calculated based on seaweed weight measurements every week during the research period. This parameter indicates the organism's ability to increase its weight per unit time. According to Mukhlis *et al* (2017) in Anggraeni Astuti et al., (2021), the formula for calculating specific growth rate is as follows:

**SGR = ((Wt/Wo)^(1/*t*) - 1) × 100%**

Where:

* SGR = Specific growth rate (%/day)
* Wt = Seedling weight at the end of the research (g)
* Wo = Seedling weight at the beginning of the research (g)
* t = Maintenance time (days)
1. **Biomass Residue**

Biomass residue is the remaining biomass that survives after a decrease in biomass amount following growth, calculated using the following formula:

**Residu biomassa (%)** $=\frac{Wf}{Wp}x100\%$

Where:

* Wf = Final weight at the end of observation (g)
* Wp = Weight achieved at peak growth (g)

**2.5.2 Supporting Parameters**

Supporting parameters in this research included water quality parameters consisting of temperature, salinity, and pH. Water quality parameter measurements were conducted to monitor cultivation environmental conditions that could affect the growth of *Caulerpa* sp. Measurements were performed once a week using the following instruments:

1. Thermometer to measure water temperature (°C)
2. Refractometer to measure salinity (ppt)
3. pH meter to measure water acidity level The measurement

data of water quality parameters were recorded in observation tables for subsequent descriptive analysis.

3. RESULTS AND DISCUSSION

**3.1 Results**

**3.1.1 Weight of *Caulerpa lentillifera* During Culture Period**

In this study, sea grapes *Caulerpa lentillifera* with an average initial weight of 3.617 to 3.882 g were cultured using 3-liter glass jars filled with 1 liter of seawater and maintained for 30 days. Weight measurements taken every 10 days showed optimal growth phase from day 10 to 20. The weight data of *Caulerpa lentillifera* during cultivation for each treatment can be seen in Figures 1 and 2.

Figure 1. Weight of *Caulerpa lentillifera*.

Figure 2. Weight of *Caulerpa lentillifera*

**3.1.1 Absolute Growth**

Absolute growth is a parameter that indicates the difference between final biomass and initial biomass of organisms during a specific maintenance period. The measurement results of absolute growth of *Caulerpa lentillifera* maintained for 45 days with different water exchange intervals showed a range of values between 207.3 mg and 504.0 mg. The absolute growth data for each treatment are presented in Figure 3.

Figure 3. Absolute Growth of *Caulerpa lentillifera*

Based on statistical analysis results, different water exchange intervals showed a significant effect (*p* < 0.05) on the absolute growth of *Caulerpa lentillifera*. The highest average absolute growth value was obtained in treatment C (10-day water exchange interval) at 504.0 mg, followed by treatment D (15-day water exchange interval) at 482.1 mg. Meanwhile, lower absolute growth values were obtained in treatment A (1-day water exchange interval) at 249.1 mg and treatment B (5-day water exchange interval) at 207.3 mg.

The Least Significant Difference (LSD) test results showed that treatment A was not significantly different from treatment B, but was significantly different from treatments C and D. This indicates that too frequent water exchange intervals (1-5 days) can inhibit the absolute growth of *Caulerpa lentillifera*. Conversely, treatment C was not significantly different from treatment D, but was significantly different from treatments A and B, indicating that longer water exchange intervals (10-15 days) provide more optimal conditions for biomass accumulation.

**3.1.2 Relative Growth**

Relative growth describes the comparison between biomass increment and initial biomass expressed as a percentage. The measurement results of relative growth of *Caulerpa lentillifera* during 45 days of cultivation with different water exchange intervals showed a range of values between 5.52% and 13.54%. The relative growth data for each treatment are presented in Figure 4.

Figure 4. Relative growth of *Caulerpa lentillifera*

Statistical analysis showed that water exchange intervals had a significant effect (*p* < 0.05) on the relative growth of *Caulerpa lentillifera*. The highest mean relative growth value was obtained in treatment D (15-day water exchange interval) at 13.54%, followed by treatment C (10-day water exchange interval) at 13.42%. Lower relative growth values were obtained in treatment A (1-day water exchange interval) at 6.42% and treatment B (5-day water exchange interval) at 5.52%.

Based on the LSD test results, treatment A was not significantly different from treatment B, but was significantly different from treatments C and D. A similar pattern was also shown where treatment C was not significantly different from treatment D, but was significantly different from treatments A and B. These results indicate that longer water exchange intervals provide better growth efficiency compared to shorter water exchange intervals.

**3.1.3 Specific Growth Rate**

Specific growth rate (SGR) is a parameter that indicates the daily growth rate of organisms expressed as a percentage per day. The measurement results of specific growth rate of *Caulerpa lentillifera* cultured for 45 days with different water exchange intervals showed a range of values between 0.269% per day to 0.635% per day. The specific growth rate data for each treatment are presented in Figure 5.

Statistical analysis results showed that water exchange intervals had a significant effect (*p* < 0.05) on the specific growth rate of *Caulerpa lentillifera*. The highest mean specific growth rate value was obtained in treatment D (15-day water exchange interval) at 0.635% per day, followed by treatment C (10-day water exchange interval) at 0.630% per day and treatment A (1-day water exchange interval) at 0.624% per day. The lowest specific growth rate value was obtained in treatment B (5-day water exchange interval) at 0.269% per day.

Based on the LSD test results, treatment A was not significantly different from treatments C and D, but was significantly different from treatment B. Treatment B showed significant differences with all other treatments (A, C, and D). These results indicate that the 5-day water exchange interval (treatment B) provided suboptimal conditions for the daily growth rate of *Caulerpa lentillifera*.

Figure 5. Specific Growth Rate of *Caulerpa lentillifera*

**3.1.4 Biomass Residue**

Biomass residue is a parameter that describes the percentage of biomass remaining after harvesting or degradation processes during the cultivation period. The measurement results of biomass residue of *Caulerpa lentillifera* cultured for 45 days with different water exchange intervals showed a range of values between 24.26% and 58.68%. The biomass residue data for each treatment are presented in Figure 6.

Figure 6. Biomass Residue of *Caulerpa lentillifera*

Statistical analysis showed that water exchange intervals had a significant effect (*p* < 0.05) on the biomass residue of *Caulerpa lentillifera*. The highest mean biomass residue value was obtained in treatment C (10-day water exchange interval) at 58.68%, followed by treatment D (15-day water exchange interval) at 41.92%. Lower values were obtained in treatment B (5-day water exchange interval) at 27.94% and treatment A (1-day water exchange interval) at 24.26%.

The LSD test results showed that treatment A was not significantly different from treatments B and D, but was significantly different from treatment C. Treatment C was not significantly different from treatment D, but was significantly different from treatments A and B. These results indicate that the 10-day water exchange interval provided optimal conditions for maintaining the biomass of *Caulerpa lentillifera* during the cultivation period.

**3.1.5 Water Quality**

Water quality is a very important environmental factor in supporting the growth and survival of *Caulerpa lentillifera* during the cultivation period. The water quality parameters observed included salinity, pH, and temperature, which were measured every 10 days during the research period. The water quality measurement results during the research activity are presented in Table 1.

Table 1. Water Quality Parameters During Research

| **No** | **Parameter** | **Obtained Range** | **Optimal Range** | **Reference** |
| --- | --- | --- | --- | --- |
| 1 | Salinity (ppt) | 30-33 | 30-37 | Sapitri et al. (2016) |
| 2 | pH | 8 | 6-9 | Risnawati et al. (2018) |
| 3 | Temperature (°C) | 28-29 | 20-31 | Firda et al. (2022) |

Based on the measurement results, all water quality parameters observed during the research were within the optimal range for *Caulerpa lentillifera* growth. Salinity ranged between 30-33 ppt, pH ranged between 7-8, and temperature ranged between 28-29°C. These stable and optimal water quality conditions support the validity of the research results, where the observed growth differences were truly caused by differences in water exchange intervals and not by fluctuations in water quality parameters.

**3.2 Discussion**

**3.2.1 Effect of Water Exchange Intervals on Growth**

The research results showed that water exchange intervals had a significant effect on the growth of *Caulerpa lentillifera*. Treatments with longer water exchange intervals (10-15 days) produced better growth compared to shorter water exchange intervals (1-5 days). This phenomenon is closely related to the principles of homeostasis and physiological adaptation of macroalgae to environmental condition changes.

Too frequent water exchange can cause physiological stress in *Caulerpa lentillifera*. According to Stigebrandt et al. (2004), macroalgae require time to adapt to environmental condition changes, and too frequent fluctuations can disrupt normal metabolic processes. This is consistent with the research results showing that treatment A (1-day interval) and B (5-day interval) provided lower growth compared to treatments C and D.

Nutrient stability in the culture medium is a key factor explaining the positive effect of treatments with longer water exchange intervals. Too frequent water exchange can eliminate nutrients that have accumulated in the culture medium, thereby reducing nutrient availability for macroalgae growth (Cole et al., 2014). Conversely, longer water exchange intervals allow *Caulerpa lentillifera* to utilize nutrients optimally in the culture medium.

Research conducted by Thi Ngoc Anh et al. (2020) showed that *Caulerpa lentillifera* responds positively to appropriate water exchange frequency regulation. Research results on the effect of water exchange frequency on sea grape growth showed that water exchange with optimal frequency provided better growth results. This supports the research results showing that 10-15 day water exchange intervals provide optimal conditions for *Caulerpa lentillifera* growth.

Energetic aspects also play an important role in explaining this phenomenon. Too frequent water exchange can cause *Caulerpa lentillifera* to allocate more energy for adaptation and homeostasis processes compared to growth. According to Littler and Littler (1980), macroalgae have different energy allocation strategies depending on environmental conditions. Under stress conditions, energy will be allocated to maintain vital cell functions rather than for growth.

The nutrient absorption mechanism by *Caulerpa lentillifera* is also influenced by environmental stability. Lindholm-Lehto (2023) stated that macroalgae absorb nutrients through their entire body surface, and this process requires time to reach equilibrium. Too frequent water exchange can disrupt this nutrient absorption process, thereby reducing the efficiency of nutrient utilization for growth.

**3.2.2 Growth Pattern Analysis Based on Parameters**

Analysis of various growth parameters showed an interesting consistency pattern. Treatment B (5-day water exchange interval) consistently provided the lowest results in almost all growth parameters, namely absolute growth (207.3 mg), relative growth (5.52%), and specific growth rate (0.269% per day). This phenomenon indicates that the 5-day water exchange interval is in the most suboptimal condition for *Caulerpa lentillifera* growth.

A unique growth pattern was observed in the specific growth rate parameter, where treatment A (1-day interval) showed relatively high values (0.624% per day) and was not significantly different from treatments C and D. This indicates that although daily water exchange can disrupt total biomass accumulation, daily growth efficiency can still be maintained. According to Walinono et al. (2017), specific growth rate reflects the intrinsic metabolic activity of macroalgae, which can differ from total biomass growth.

The pattern differences between absolute growth and specific growth rate indicate a trade-off between metabolic efficiency and biomass accumulation. Research on macroalgae shows that high water exchange rates can provide constant nutrient supply but can also prevent optimal biomass accumulation (Cole et al., 2014). This explains why treatment A can maintain high specific growth rates but produce low absolute growth.

The relative growth parameter showed a pattern similar to absolute growth, where treatments C and D provided significantly higher results compared to treatments A and B. Relative growth reflects the efficiency of initial biomass utilization to produce new biomass. The high relative growth values in treatments C (13.42%) and D (13.54%) indicate that longer water exchange intervals allow *Caulerpa lentillifera* to utilize initial biomass more efficiently.

Biomass residue showed a slightly different pattern, where treatment C provided the highest value (58.68%) followed by treatment D (41.92%). This parameter reflects the ability of *Caulerpa lentillifera* to maintain biomass during the cultivation period. The high biomass residue value in treatment C indicates that the 10-day water exchange interval provides optimal conditions for maintaining cell structure integrity and preventing biomass degradation.

The inconsistency pattern in the biomass residue growth parameter can be explained through the concept of physiological response curves. According to Duarte et al. (2017), macroalgae response to environmental factors generally follows an optimum curve, where there is an optimal point that provides maximum response. In this case, the 10-day water exchange interval (treatment C) appears to be the optimal point for maintaining biomass residue, while longer intervals (15 days) may begin to show negative effects due to metabolite accumulation or water quality deterioration.

Variation in response among growth parameters also reflects the complexity of physiological processes in *Caulerpa lentillifera*. Each growth parameter is influenced by different physiological factors, such as photosynthesis activity, respiration, nutrient absorption, and protein synthesis. Dawes (1998) stated that macroalgae growth is the result of integration of various metabolic processes that can provide different responses to the same environmental factors.

The results of this analysis show that macroalgae growth evaluation should be conducted using multiple parameters to obtain a comprehensive picture of the organism's physiological condition. The use of single parameters can provide biased information and does not reflect actual growth conditions.

**3.2.3 Physiological and Ecological Aspects**

The research results showed that water exchange intervals had a significant effect on *Caulerpa lentillifera* growth, with 10-15 day intervals (treatments C and D) providing the best performance compared to shorter intervals. This phenomenon can be explained through several physiological and ecological aspects underlying the adaptation mechanisms of macroalgae to environmental changes.

**Physiological Adaptation Mechanisms**

*Caulerpa lentillifera* as a green macroalga has high adaptability to aquatic environmental fluctuations (Paul et al., 2006). Too frequent water exchange can cause physiological stress in organisms through sudden changes in physical-chemical parameters of water. According to Kumar et al. (2011), macroalgae undergo acclimatization processes that require metabolic energy to adjust their physiological systems to new environmental conditions. In this study, treatments A and B (1-5 day intervals) showed lower growth, possibly due to excessive energy allocation for adaptation processes rather than for growth.

*Caulerpa lentillifera* has tolerance mechanisms to dehydration stress involving changes in chlorophyll fluorescence parameters and increased antioxidant compounds. This indicates that this species has a complex defense system against environmental stress. Optimal water exchange (10-15 days) provides sufficient time for the organism to perform physiological stabilization without experiencing excessive stress.

**Relationship with Nutrient Balance**

An important ecological aspect in this study is the relationship between water exchange intervals and nutrient availability and stability in the culture medium. *Caulerpa lentillifera* has effective capability in absorbing inorganic nutrients from the aquatic environment, including nitrogen, phosphorus, and potassium. Too frequent water exchange can cause nutrient availability fluctuations that disrupt nutrient absorption and metabolism processes.

According to Liang et al. (2019), macroalgae require time to optimize their nutrient absorption systems according to nutrient concentrations in the environment. The 10-15 day water exchange interval provides opportunities for *Caulerpa lentillifera* to maximize absorption of added nutrients (N 30 ppm, P 4 ppm, K 6 ppm) before the next water exchange.

**Photosynthesis and Metabolism Processes**

The photosynthesis efficiency of macroalgae is on average three to four times higher than terrestrial biomass, indicating the importance of environmental stability to maintain optimal photosynthesis processes. Too frequent water exchange can disrupt the balance of microorganisms and suspended particles that can affect light penetration into the culture medium.

The stability of water quality parameters observed in the study (salinity 30-33 ppt, pH 7-8, temperature 28-29°C) supports optimal photosynthesis processes. *Caulerpa lentillifera* is rich in proteins, minerals, dietary fiber, vitamins, and fatty acids produced through efficient metabolic processes, so stable environmental conditions are required to maintain the quality of these metabolic processes.

**Bioremediation and Detoxification Capacity**

Another ecological aspect that needs to be considered is the ability of *Caulerpa lentillifera* as a bioremediator. *Caulerpa lentillifera* can remove more than 90% of steroid hormones (E2 or EE2) at concentrations of 10 µg/L within 12 hours through biosorption, accumulation, and biodegradation processes. This bioremediation capability requires time to work optimally, so longer water exchange intervals provide opportunities for organisms to perform environmental cleaning functions more effectively.

**3.2.4 Comparison with Previous Research**

Research on the effect of water exchange intervals on macroalgae growth is still limited in scientific literature. However, several related studies provide perspectives that support the findings of this research. Comparative studies of macroalgae cultivation systems show that different cultivation platforms and cultivation strategies provide different economic and environmental impacts, indicating the importance of optimizing cultivation parameters.

**Research on Other Caulerpa Species**

*Caulerpa lentillifera*, known as "sea grapes" or "green caviar," is an edible green macroalga with distinctive texture and various nutritional benefits. Previous research has focused more on nutritional aspects and post-harvest processing, while research on cultivation parameter optimization still requires further development.

**Integrated Aquaculture System Studies**

The polyculture system of *Caulerpa lentillifera* with white shrimp (*Litopenaeus vannamei*) demonstrates a strategic approach for sustainable shrimp production. That research showed that *Caulerpa* can function as a biofilter in aquaculture systems, supporting the findings of this research that optimal water exchange intervals are important for maintaining the ecological function of macroalgae.

**Comparison with Other Macroalgae**

Multi-scale models for *Ulva* sp. macroalgae growth and nitrogen sequestration show that macroalgae growth is regulated by temperature, light, and nutrients. Although conducted on different species, that research supports the importance of environmental parameter stability for optimal macroalgae growth, which aligns with the findings of this research on *Caulerpa lentillifera*.

**Cultivation Technology Aspects**

Marine macroalgae have long been considered an important source of nutrition, especially in Asian countries, and subsequently gained attention in Europe. Development of more robust and cost-efficient advanced cultivation technologies is crucial for farming systems, especially for highly exposed offshore environments. The findings of this research contribute to the development of more efficient cultivation protocols.

**Research Gaps and Contributions**

Based on literature review, research on the specific effect of water exchange intervals on *Caulerpa lentillifera* growth is still very limited. Most previous research focused on nutritional aspects, bioactivity, and applications in integrated aquaculture systems. This research provides important contributions in:

1. **Cultivation Parameter Optimization**: Providing optimal water exchange interval recommendations (10-15 days) for *Caulerpa lentillifera* cultivation.
2. **Comprehensive Approach**: Using multiple growth parameters (absolute, relative, SGR, and biomass residue) for more thorough evaluation.
3. **Practical Applications**: Providing scientific basis for developing cultivation protocols that are more operationally and economically efficient.

**Implications for Future Research**

Seaweed cultivation has attracted significant attention due to various biomass benefits, but comprehensive assessment from various perspectives is crucial to ensure sustainable seaweed cultivation. This research opens opportunities for further studies that integrate economic, environmental, and social aspects in the development of *Caulerpa lentillifera* cultivation technology.

**3.2.5 Practical Implications in Cultivation**

* **Operational and Economic Efficiency**

Research results showed that 10-15 day water exchange intervals provide optimal growth for *Caulerpa lentillifera*, which makes a significant contribution to commercial cultivation development. Commercial cultivation of *C. lentillifera* began in the early 1950s on Mactan Island, Cebu Province, Central Visayas, Philippines, and has since expanded to various countries including Japan in 1968, Vietnam, Taiwan, and China.

From an operational efficiency perspective, 10-15 day water exchange intervals provide several practical advantages:

1. **Workload Reduction**: Longer intervals reduce water exchange frequency from 30 times per month (1-day interval) to only 2-3 times per month (10-15 day intervals), significantly reducing labor requirements and operational costs.
2. **Nutrient Utilization Efficiency**: *Caulerpa lentillifera* can function as a biofilter in aquaculture systems, so longer intervals provide sufficient time to utilize added nutrients before the next water exchange.
3. **Cultivation System Stability**: Too frequent water exchange can cause water quality parameter fluctuations that can disrupt overall cultivation system stability.
* **Scalability for Commercial Cultivation**

Green seaweed is still underrepresented compared to red and brown macroalgae in global marine aquaculture production, so optimization of *Caulerpa lentillifera* cultivation parameters has great potential for industry development. Global food production faces challenges due to natural agricultural boundaries and crises such as climate change, so edible seaweed cultivation is discussed as part of the solution to provide healthy food produced sustainably.

The findings of this research can be applied in:

1. **Pond Cultivation Systems**: Water exchange interval recommendations can be applied in traditional pond cultivation systems that have developed in Southeast Asia.
2. **Integrated Aquaculture Systems**: *Caulerpa* has proven effective in filtering water used in fish, mollusc, and shrimp cultivation, particularly *C. lentillifera*, so these research results can support polyculture system development.
3. **Industrial Scale Cultivation**: Optimal water exchange intervals can be integrated into larger mechanical cultivation systems with automatic control.
* **Economic and Sustainability Aspects**

*Caulerpa lentillifera* cultivation has high economic value due to its rich content of protein, minerals, dietary fiber, vitamins, and saturated fatty acids. Optimization of water exchange intervals can improve:

1. **Biomass Productivity**: With absolute growth reaching 504.0 mg at 10-day intervals, productivity per cultivation unit area can be significantly increased.
2. **Cost Efficiency**: Reduced water exchange frequency can lower operational costs, especially in terms of energy consumption for water pumps and labor costs.
* **Applications in Bioremediation Systems**

Dried seaweed can be used as a biosorbent for heavy metals and cationic dyes, while fresh seaweed can function as a biofilter for aquaculture systems. Optimal water exchange intervals allow *Caulerpa lentillifera* to perform bioremediation functions more effectively, which has implications for:

1. **Wastewater Treatment**: Cultivation systems can be designed to simultaneously perform wastewater treatment from other aquaculture activities.
2. **Sustainable Agriculture**: The use of *Caulerpa* as biofertilizer has been studied particularly in India, where fertilizer consisting of 25% *Caulerpa* extract enhances growth.

**3.2.6 Water Quality**

Water quality is the key to every aquaculture cultivation conducted; the closer it approaches the living condition requirements of cultured organisms, the more optimal the results will be obtained. Water quality measurements in this study were conducted every 10 days during the 30-day research period. The water quality parameters measured were salinity, pH, and temperature.

The salinity range of 30-32 ppt recorded in this study was within the optimal range for sea grape growth. Research shows that *C. lentillifera* can survive at salinity levels of 20-50 ppt and can develop well at salinity levels of 30-40 ppt, with maximum specific growth rate occurring at 35 ppt salinity (Chen et al., 2019). The salinity values obtained were very close to these optimal conditions, indicating that the cultivation system successfully maintained environmental conditions that support sea grape growth.

Previous studies showed that maximum specific growth rate was obtained at 35 ppt salinity, which is consistent with maximum chlorophyll content and fluorescence ratio (Stuthmann et al., 2023). Stable salinity in the range of 30-32 ppt allows sea grapes to maintain optimal osmotic balance, supporting efficient photosynthesis processes and cellular metabolism.

The temperature range of 28-29°C recorded in this study was in very optimal conditions for *C. lentillifera* growth. Stable water quality parameters with temperatures ranging from 28-30°C have been proven to support sea grape growth. Temperature stability in this range is important because it affects enzyme activity involved in photosynthesis and metabolism processes.

Research on *Caulerpa* species shows that optimal growth occurs at temperatures of 23-26°C, with an average of 16% at 23°C and 48% at 26°C (Apriliyanti et al., 2024). The temperature of 28-29°C obtained in this study was slightly higher but still within good tolerance limits for tropical species such as *C. lentillifera*.

Consistent temperature in this range allows sea grapes to maintain optimal metabolic rates, support photosynthesis processes, and facilitate efficient nutrient absorption. Temperature is one of the most important factors affecting the growth of *Caulerpa lentillifera* (Liang et al., 2019).

The pH range of 7-8 recorded showed optimal conditions for sea grape cultivation. Stable pH conditions in the range of 7.5-7.8 have been proven to support *C. lentillifera* growth. pH in this range indicates slightly alkaline to neutral conditions, which are optimal conditions for most biochemical processes in sea grape cells.

Stable pH in the range of 7-8 supports nutrient availability in forms that can be absorbed by sea grapes, especially nitrogen and phosphorus which are important for growth. These pH conditions also facilitate photosynthesis processes by maintaining the balance of carbonate and bicarbonate ions in the cultivation medium.

Overall, the recorded water quality parameters (salinity 30-32 ppt, temperature 28-29°C, pH 7-8) showed environmental conditions that were very supportive for *C. lentillifera* growth. The stability of these three parameters in optimal ranges explains why this study successfully achieved good growth rates across various water exchange treatments.

The consistency of these water quality parameters also indicates that the cultivation system used has good buffering capacity, so changes in water exchange frequency do not cause extreme fluctuations in water quality parameters. This is important to ensure that the observed differences in growth results are truly caused by water exchange treatments, not by water quality variations.

1. **Conclusion**

The conclusions from this research are:

* Treatment with a 10-day water exchange interval (C) had a significant effect on the growth of *Caulerpa lentillifera*, where the 10-day water exchange interval produced the highest growth with absolute growth values of 504.0 mg, relative growth rate of 13.42%, and daily specific growth rate of 0.630% per day.
* The 10-day water exchange interval (C) growth was not significantly different from the 15-day water exchange interval (D) but was significantly different from the daily interval treatment (A) and the 5-day water exchange interval treatment (B).
* The treatment with a 10-day water exchange interval resulted in the highest biomass residue of 58.68%, which was not significantly different from treatment D but was significantly different from treatments A and B.
* The water quality parameters (salinity 30–32 ppt, temperature 28–29°C, and pH 7–8) indicated optimal and stable conditions for the growth of sea grapes across all treatments.
* Water exchange every 10 days (treatment C) was the most effective method for cultivating Caulerpa lentillifera, providing maximum biomass productivity with good operational efficiency.

COMPETING INTERESTS DISCLAIMER:

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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