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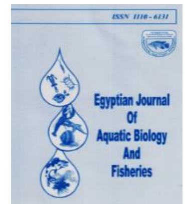

Effectiveness of Nitrogen (N) and Phosphorus (P) Absorption and Growth Performance of *Gracilaria* sp., *Kappaphycus alvarezii*, and *Caulerpa* sp. in Shrimp Aquaculture Wastewater

Nurhani Supardi[1], Kukuh Nirmala[1], Eddy Supriyono[1], Rachman Syah[2]

[1]Departmen of Aquaculture, Faculty of Fisheries and Marine Sciences, IPB University (Bogor Agricultural University), Dramaga, Bogor 16680, Indonesia
[2]National Research, and Innovation Agency (BRIN), Cibinong, Bogor, Jawa Barat 16911, Indonesia

[*]Corresponding Author: nurhanisupardi1105@gmail.com

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ABSTRACT

Intensive shrimp farming produces nitrogen (N) and phosphorus (P) waste, which can cause eutrophication and decrease water quality if not managed properly. Therefore, an effective bioremediation strategy is required to reduce the negative impact of aquaculture waste. Seaweed is an aquatic organism capable of absorbing nutrients from water, making it a potential bioremediation agent in sustainable aquaculture. This study aimed to analyze the effectiveness of N and P absorption and the growth performance of *Gracilaria* sp., *Kappaphycus alvarezii*, and *Caulerpa* sp. in treating shrimp culture wastewater. The research method used a Completely Randomized Design (CRD) with five replications. Data on nutrient absorption rates and seaweed growth were analyzed using analysis of variance (ANOVA) at a 95% confidence level, followed by Duncan's Advanced Test. The results showed that *Caulerpa* sp. had the highest daily growth rate and nutrient absorption efficiency compared to *Gracilaria* sp. and *K. alvarezii* (P<0.05). *Caulerpa* sp. demonstrated superior ability in absorbing nitrogen, with a phosphate absorption rate of 0.093 mg/m²/day, significantly higher than *Gracilaria* sp. at 0.029 mg/m²/day (P<0.05). With its superior bioremediation ability, *Caulerpa* sp. has the potential to be a natural solution for managing shrimp aquaculture wastewater, improving the sustainability of aquaculture systems, and reducing environmental pollution.

INTRODUCTION

Aquaculture activities, particularly shrimp farming, generate significant amounts of nitrogen (N) and phosphorus (P) waste **(Komarawidjaja, 2005)**. According to **Skriptsova and Miroshnikova (2011)**, nitrogen and phosphorus are the primary nutrients present in aquaculture waste and can become environmental contaminants at high concentrations. **Syah *et al.* (2014)** stated that super-intensive vannamei shrimp ponds with a stocking density of 500 individuals/m² produce waste containing 50.12 gTN/kg shrimp, 15.73 gTP/kg shrimp, and 126.85 gC/kg shrimp. Similarly, **Rachmansyah *et al.* (2006)** found that vannamei shrimp farming with a stocking density of 50 individuals/m² resulted in 32.87-37.23% total nitrogen and 16.46%-18.15% total phosphorus. Shrimp aquaculture wastewater contains nitrogen in the form of NH_3 (ammonia), NO_3 (nitrate), and NO_2 (nitrite) as byproducts of protein and amino acid breakdown from feed and feces **(Harahap, 2019)**. Wastewater from ponds can disrupt the life of fish or other aquatic organisms in public waters and can also lead to increased fertility of phytoplankton or aquatic plants.

Seaweed is an aquatic plant that can capture macronutrients and metal contaminants from the environment; therefore, it is increasingly used in the phytoremediation of polluted seawater **(Neori *et al.,* 2004)**. In Indonesia, seaweed is quite abundant, with the largest production in South Sulawesi, amounting to 3.796.882 tons per year **(Ministry of Marine Affairs and Fisheries of Indonesia, 2023)**. **Stowell *et al.* (2000)** stated that seaweed generally has the ability to neutralize certain components in the water, which is very beneficial in the treatment of wastewater. The organic material stored within seaweed cells eventually degrades through photosynthesis, assisted by sunlight. This process generates energy and cells that reflect the growth of seaweed plants **(Burken & Schnoor, 1997)**. **Akhrari (2013)** also stated that seaweed plays an ecological role by absorbing nitrogen in the form of NH_3 and NO_3 through its thallus and is capable of photosynthesis, which produces oxygen.

Seaweed has been shown to outperform bacterial filters in nitrogen absorption. Ammonium levels in water are lower when using seaweed as a filter, whereas nitrate levels increase over time with recirculation using bacterial filters **(Cahill *et al*., 2010)**. According to **Yuniarsih *et al.* (2014)**, nitrogen is essential in water as it is a nutrient that triggers the growth of seaweed. This is supported by **Syah *et al.* (2017)**, who stated that the presence of *Gracilaria* sp. in equalization ponds contributes to the absorption of N and P and functions as a trap for colloidal particles in wastewater. **Herlinah *et al.* (2017)** found that the absorption rate of N in the form of nitrate (NO_3) by *K. alvarezii* seaweed within 24 h could reach 24.8 μg/g dry weight. These results are similar to those of **Pramita (2022)**, who found that the application of liquid organic fertilizer in *Caulerpa racemosa* seaweed cultivation media significantly affected absolute weight growth and absolute length growth rates. The best absolute weight growth and absolute length growth rates of *C. racemosa* were obtained at a liquid organic fertilizer concentration of 0.34 mL fertilizer/L water (the highest concentration in their study).

This indicates that the ability of seaweed to filter dissolved materials from wastewater has the potential to be part of aquaculture waste management efforts. By studying the absorption rates of *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp., this study aimed to provide information on the use of seaweed as a bioremediator in coastal areas integrated with shrimp farming. In addition, the current work was organized to analyze the nitrogen (N) and phosphorus (P) absorption rates of *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp. in shrimp aquaculture wastewater.

MATERIALS AND METHODS

Description of the study site

This study was conducted from August to October 2024 at the Experimental Pond Installation of the Brackishwater Aquaculture Research and Fisheries Extension Center (BRPBAP3), Punaga Village, Mangarabombang District, Takalar Regency, South Sulawesi Province. Proximate analysis was conducted at the Feed Chemistry Laboratory of the Faculty of Animal Husbandry, Hasanuddin University.

Experimental materials and research design

The *Gracilaria* sp. seaweed used in this study originated from Ujung Baji Village, Sanrobone District, Takalar Regency, Indonesia. *K. alvarezii* and *Caulerpa* sp. seaweed originated from Laikang Village, Laikang District, Takalar Regency, South Sulawesi Province. Research Design The research design was an experimental method using a Completely Randomized Design with three treatments. The seaweed biomass used was 4 g L^{-1} **(National standardization Agency of Indonesia, 2010)**. The seaweed species used were *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp. Each seaweed species was used with an initial biomass of 200g and replicated thrice.

Research procedure

The research was conducted in a wet lab Brackishwater Aquaculture Research and Fisheries Extension Center (BRPBAP3), Punaga Village, Mangarabombang District, Takalar Regency, South Sulawesi Province, a closed room still exposed to sunlight to allow photosynthesis and to prevent significant temperature fluctuations. Maintenance containers used 60 × 30 × 50 cm aquariums equipped with an aeration system supplied by a blower for oxygen supply **(Yuniarti *et al.*, 2019)**. The aquariums were cleaned, drained, and filled with 50L of vannamei shrimp farming wastewater from the Experimental Pond Installation at BRPBAP3, Takalar Regency, South Sulawesi Province. *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp. seaweed were selected and sorted in the morning in a shaded area to avoid direct sunlight. The selected seaweed was fresh, not wilted, and had a firm texture. The seaweed was cleaned of macrozoobenthos, mud, moss, and snails. The seaweed was weighed according to a treatment weight of 4 g/L **(National standardization Agency of Indonesia, 2010)**. Maintenance was performed for 28 days. Before maintenance, each seaweed species (*Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp.) was acclimatized for 24h to gradually adapt to environmental changes, such as temperature, humidity, pH, and salinity **(Yong *et al.*, 2015)**. Before maintenance, the nitrogen (N) and phosphorus (P) levels were tested. The seaweed was weighed on an electronic scale. The cleaned seaweed was spread using the bottom-spreading method, with seaweed seeds spread at the bottom of the aquariums. During maintenance, 50L of shrimp farming wastewater was added to the maintenance medium, followed by the addition of 200g of seaweed per aquarium. Sampling during maintenance included daily growth rate, nitrogen and phosphorus absorption rates, and physicochemical water parameters such as salinity, pH, temperature, DO, ammonia, nitrite, nitrate, and phosphate.

Daily growth rate

The daily growth rate is the average weight change of seaweed from the beginning to the end of maintenance. A digital scale was used to obtain the daily growth weight of the seaweed. The wet weight of the seaweed was cleaned, weighed, and analyzed using the following equation **(Hung *et al.*, 2009)**.

$$DGR\ (\%) = \{[Wt / Wo]1/t - 1\} \times 100$$

Notes: Daily Growth Rate (DGR),
Final average weight (Wt),
Initial average weight (Wo), and
Maintenance time (t)

Nitrogen and phosphorus absorption rate

The nitrogen and phosphorus absorption rates are the amounts of nitrogen and phosphorus absorbed by seaweed per maintenance area. The nitrogen and phosphorus absorption rates of the seaweed were observed weekly. The absorption rates were calculated using the following formula **(Kitadai & Kadowaki, 2007)**.

$$Pob = \{(C_t - C_o) \times \alpha\}/t$$

Notes: Nitrogen and phosphorus absorption rate in $mg/m^2/day$ (Pob),
Initial nitrogen and phosphorus content in seaweed in mg DW g^{-1} (Co),
Final nitrogen and phosphorus content in seaweed in mg DW g^{-1} (Ct),
Final dry biomass of seaweed in g m^{-2} (α), and
Maintenance duration in days (t).

Water quality parameters

Water quality parameters were measured to determine the condition of the maintenance media during the study. However, nitrate, nitrite, ammonia, and phosphate levels were measured as indicators of nutrient availability in the maintenance media derived from shrimp farming wastewater.

Table 1. Water quality measurement parameters for seaweed maintenance

Parameter	Type of sample	Equipment	Unit
Total N	Seaweed	Kjeldahl	%
Total P	Seaweed	Spectrophotometer	%
Salinity	Aquaculture waste water	Refractometer	g L^{-1}
DO	Aquaculture waste water	DO meter	mg L^{-1}
Temperature	Aquaculture waste water	Thermometer	^0C
pH	Aquaculture waste water	pH meter	unit
Nitrite	Aquaculture waste water	Spectrophotometer	mg L^{-1}
Nitrate	Aquaculture waste water	Spectrophotometer	mg L^{-1}
Amonnia	Aquaculture waste water	Spectrophotometer	mg L^{-1}
Phosphate	Aquaculture waste water	Spectrophotometer	mg L^{-1}

Data analysis

The absorption rates and growth of seaweed were statistically tested using analysis of variance (ANOVA) at a 95% confidence level using SPSS 26.0 software. If the data showed significant differences, Duncan's test was performed. Water quality data were analyzed descriptively using tables and graphs.

RESULTS

Daily growth rate

The results showed changes in the final weights of *Gracilaria* sp. and *Caulerpa* sp. at 167.98±59.99 and 255.18±11.93, respectively. The daily growth rates of *Gracilaria* sp. and *Caulerpa* sp. in shrimp farming wastewater are shown in Fig. (1). Overall, *Caulerpa* sp. showed a significantly higher daily growth rate (P<0.05) than *Gracilaria* sp.

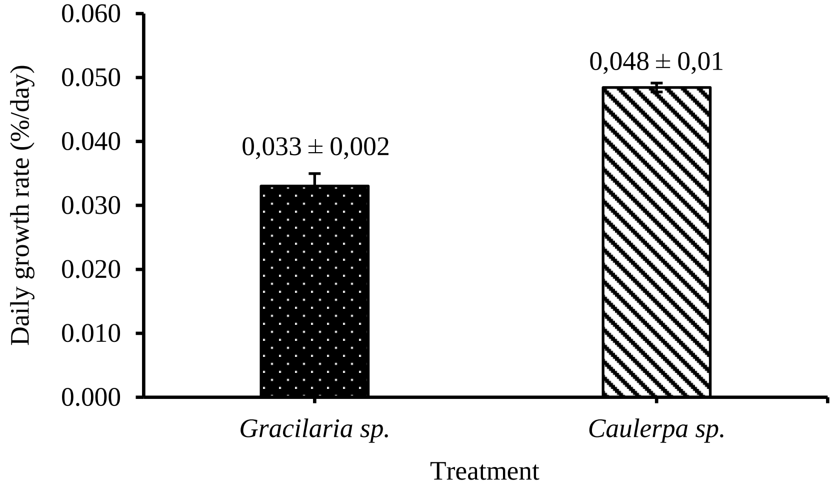


Fig. 1. Daily growth rate (%/day) of *Gracilaria* sp. and *Caulerpa* sp.

This study revealed that *Caulerpa* sp. has a higher daily growth rate than *Gracilaria* sp. The data showed that the daily growth rate of *Caulerpa* sp. reached 0.048% per day, whereas that of *Gracilaria* sp. was only 0.033% per day.

Nitrogen and phosphorus absorption rates

The use of different seaweed species in shrimp farming wastewater resulted in significant differences in nitrogen absorption rates (P<0.05). *Caulerpa* sp. showed the highest absorption rate compared to *Gracilaria* sp. (Fig. 2). Furthermore, the phosphorus content in *Caulerpa* sp. was relatively higher than that in *Gracilaria* sp. (P<0.05).

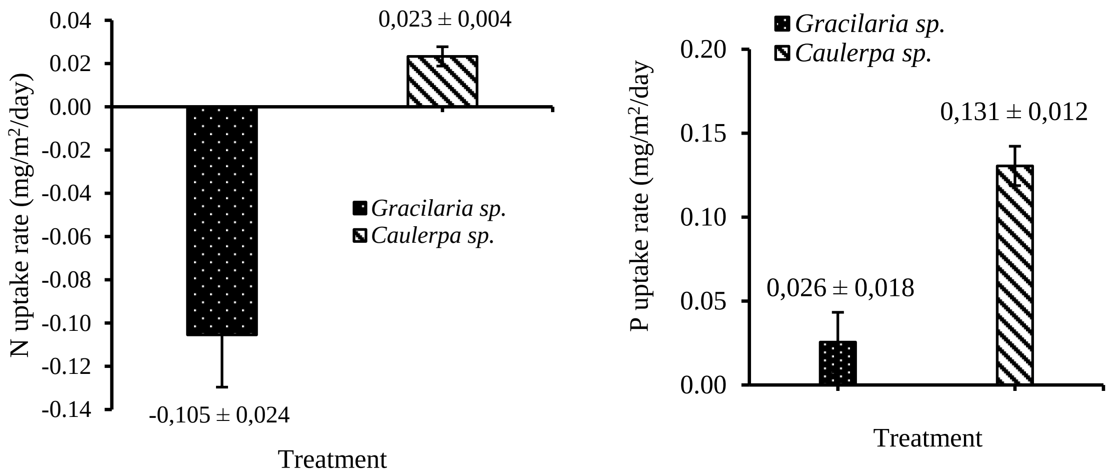
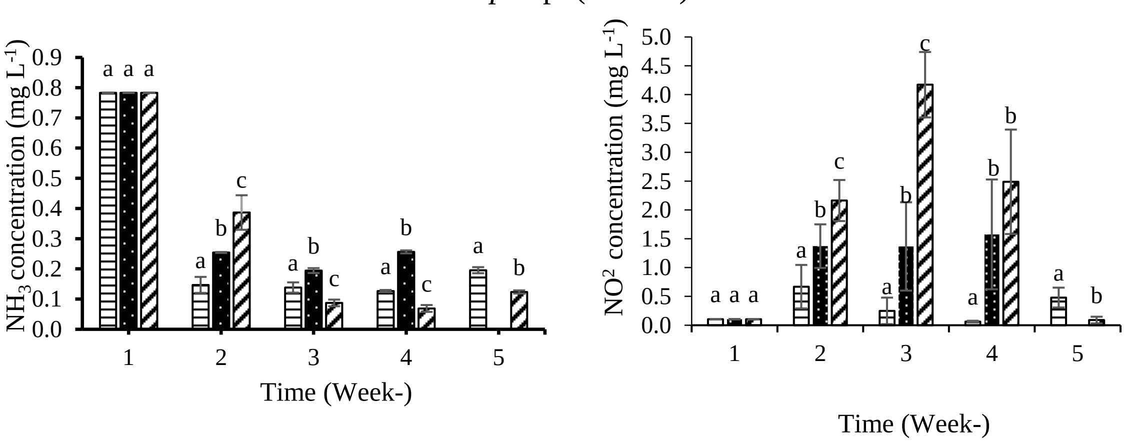


Fig. 2. Nitrogen (N) and phosphorus (P) absorption rates

The graph shows that the nitrogen (N) absorption rate of *Gracilaria* sp. was negative (-0.105±0.024 mg/m²/day) because the final weight was lower than the initial weight. In contrast, *Caulerpa* sp. showed an absorption rate of 0.023±0.004 mg/m²/day. Meanwhile, the phosphorus (P) absorption rate by *Gracilaria* sp. was 0.026±0.018 mg/m²/day, lower than *Caulerpa* sp. at 0.131±0.012 mg/m²/day. This indicates the potential of *Caulerpa* sp. as a superior phytoremediation agent in aquaculture systems.

Weekly nitrogen and phosphate concentrations in maintenance media

One-way ANOVA results showed that NH_3 concentrations from Week 2 to the end of maintenance differed significantly among the treatments (P<0.05). Furthermore, NO_2 concentrations in *Gracilaria* sp. differed significantly from *K. alvarezii* and *Caulerpa* sp. in Week 4 (P<0.05). NO_3 concentrations varied among the seaweed species. In Week 1, all treatments showed the same initial concentration of 0.201. From weeks 2 to 3, significant differences were observed between the treatments (p<0.05). In Week 3, the maintenance media for *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp. showed no significant differences (P>0.05). In Week 4, PO_4 concentrations in *Gracilaria* sp. were significantly different from those *in K. alvarezii* and *Caulerpa* sp. (P<0.05).



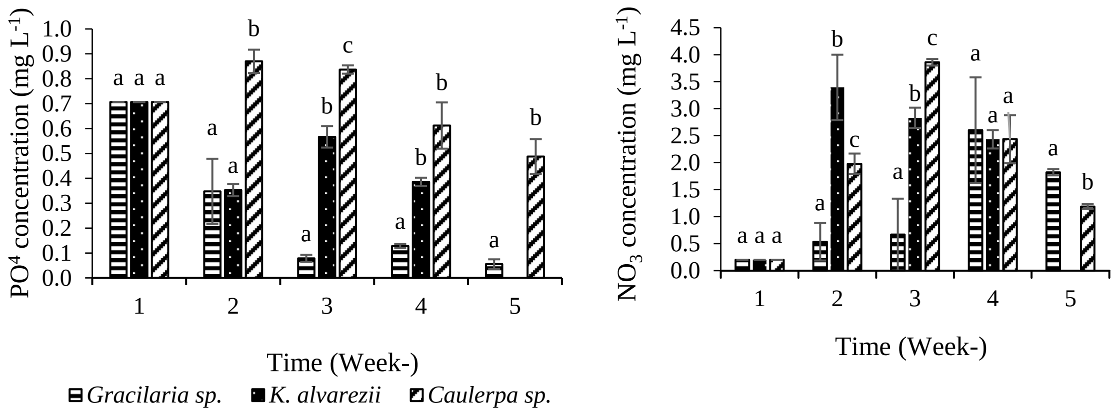


Fig. 3. Changes in NH_3, NO_2, NO_3, and PO_4 concentrations (mg L^{-1})

The results showed that NH_3 concentrations in *Caulerpa* sp. consistently decreased from 0.783 in week 1 to 0.114±0.005 in week 5. Meanwhile, *K. alvarezii* showed fluctuating absorption patterns for NH_3 concentrations. NH_3 concentrations in *K. alvarezii* maintenance media decreased from 0.783 in week 1 to 0.194±0.008 in week 3 but increased to 0.256±0.005 in week 4. By week 5, *K. alvarezii* had died, and no further data were collected. In *Gracilaria* sp., NH_3 concentrations also fluctuated, increasing to 0.196±0.010 by the end of the study NO_2 concentrations in *Caulerpa* sp. decreased from week 3 to 5, from 4.172±0.567 to 0.090±0.058. In *Gracilaria* sp., NO_2 concentrations consistently decreased from week 2 to 4, from 0.669±0.377 to 0.063±0.015. Meanwhile, NO_2 concentrations in *K. alvarezii* decreased from week 2 to 3, from 1.372±0.378 to 1.367±0.766, but increased to 1.576±0.952 in week 4. By the end of the study, NO_2 testing was discontinued because of the death of *K. alvarezii*.

K. alvarezii recorded the highest NO_3 concentration in week 2 at 3.394±0.605, followed by *Caulerpa* sp. at 1.978±0.191, and *Gracilaria* sp. at 0.536±0.348. By week 3, *Caulerpa* sp. showed an increase in concentration to 3.859±0.061, which then decreased to 1.188±0.051 by the end of the study. In *K. alvarezii*, NO_3 concentrations decreased to 2.433±0.170 by week 4. In contrast, *Gracilaria* sp. showed an increase in NO_3 concentrations, reaching 1.822±0.057 by the end of the study.

The PO_4 concentration in *Caulerpa* sp. decreased from 0.707 in week 1 to 0.487±0.070 by the end of the study. Meanwhile, *Gracilaria* sp. showed stable PO_4 absorption throughout the maintenance period. From week 1 to week 5, PO_4 concentrations in the *Gracilaria* sp. maintenance media decreased from 0.707 to 0.055±0.019. In *K. alvarezii*, PO_4 concentrations consistently decreased from week 1 to week 4, from 0.707 to 0.386±0.16 by the end of the study.

Water quality measurements in maintenance media

Water quality were measured daily in the morning and the evening. Salinity and temperature in the maintenance media fluctuated significantly. DO and pH remained within the ideal range until the end of the study (Table 3).

Table 3. Water quality in maintenance media

Parameter	Treatments					
	***Gracilaria* sp.**		***K. alvarezii***		***Caulerpa* sp.**	
	Actual	**SNI**	**Actual**	**SNI**	**Actual**	**SNI**
Salinity (ppt)	32,23 – 37,78	15 – 30	32,11 – 37,06	24 - 34	32,54 – 38,09	28 – 45
DO (mg L^{-1})	4,14 – 6,29	3,0 – 8,0	4,14 – 6,43	3,0 - 8,0	4,48 – 6,43	3,0 – 8,0
Temperature (ºC)	24,1 – 28,7	28 – 30	24,2 – 28,8	26 – 32	24,1 – 28,8	28 – 30
pH	8,1 – 8,6	6 – 9	7,8 – 8,5	7 – 8,5	7,6 – 8,5	6 – 9

Note : National standardization Agency of Indonesia (SNI)

The results showed that the water quality of shrimp farming wastewater varied as a growth medium for *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp. Salinity levels for *Gracilaria* were 32,23 – 37,78ppt and fell to 32,11 – 37,06ppt for *K. alvarezii* sp., while for *Caulerpa* sp. the levels were 32.54– 38.09ppt. Meanwhile, DO, temperature, and pH for all three seaweed species ranged from 4.14–6.43 mg L^{-1}, 21.1–28.8°C, and 7–8.6, respectively, within SNI standards. Overall, these results indicate that *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp. have good adaptability to variations in the quality of shrimp farming wastewater.

DISCUSSION

Shrimp aquaculture effluent contains high levels of nitrogen (N) and phosphorus (P) in the form of dissolved nutrients. The feed conversion ratio (FCR) ranging from 1.2 to 1.5 for 40% protein feed in shrimp farming potentially produces 48-70 kg of nitrogen per ton of shrimp **(Badraeni *et al*., 2020)**. This organic waste generates inorganic nitrogen compounds that are toxic to shrimp and lead to a decline in water quality **(Bambaranda *et al*., 2019b)**. High concentrations of inorganic nitrogen can be utilized by seaweed through bioremediation processes, as seaweed absorbs dissolved nutrients as a source of biomass formation **(Wang *et al*., 2012)**. This is supported by **Reid *et al*. (2020)**, who revealed that decomposed organic matter in inorganic forms, such as ammonium (NH_4^+), nitrate (NO_3^-), and orthophosphate (PO_4^{3-}), can be absorbed by seaweed for growth **(Reid *et al*., 2020)**. Seaweed can absorb nitrogen from water in the form of NO_3^- and NH_4^+ through active transport and passive diffusion in thallus tissue. According to **Wang *et al*. (2018)**, nitrate entering the cells is reduced to nitrite by the enzyme nitrate reductase and is further converted into ammonia, which is a usable form of nitrogen for the synthesis of proteins, enzymes, and photosynthetic pigments. This is corroborated by **Adharini *et al*. (2021)**, who confirmed that seaweed can reduce nitrogen levels by up to 80% in hybrid grouper aquaculture effluents.

The results indicate that *Caulerpa* sp. has the highest daily growth rate of 0.048%/day, compared to *Gracilaria* sp., which only reaches 0.033%/day. These growth rates are lower than those reported by **Liu *et al*. (2016)**, who found that *Caulerpa lentillifera* had a daily growth rate of 3.99%/day, while *Gracilaria lichenoides* had a rate of 3.94%/day when cultivated in seawater. This difference suggests that *Caulerpa* sp. has better growth potential under the environmental conditions used in both studies than *Gracilaria* sp. and confirms that growth tends to decrease when cultivated in shrimp aquaculture effluent compared to seawater.

Kappaphycus alvarezii experienced mortality in week 4 due to ice-ice disease, which was caused by environmental changes such as salinity exceeding the tolerance threshold (37.06 ppt.) and minimal water movement. **Aris *et al*. (2021)** reported that salinity >34 ppt leads to a reduction in the weight of *K. alvarezii* due to metabolic disturbance. **Astriana *et al*. (2019)** confirmed that salinity changes can trigger ice-ice disease. Additionally, limited water movement affects the nutrient supply to seaweed **(Serdiati & Widiastuti, 2010)**.

This study examined the effectiveness of nitrogen and phosphorus absorption by *Gracilaria* sp. and *Caulerpa* sp. in shrimp aquaculture effluent. The results showed that the nitrogen absorption rate of *Caulerpa* sp. was higher, at 0.023±0.004 mg/m²/day, compared to *Gracilaria* sp., which indicated nitrogen release into the medium with a negative value of -0.105±0.024 mg/m²/day. This aligns with **Liu *et al*. (2016)**, who stated that *C. lentillifera* is more effective at absorbing NO_3-N than *G. lichenoides*. This suggests that shrimp aquaculture effluent can be used with *Caulerpa* sp. in a phytoremediation scheme to reduce nitrogen levels in the cultivation medium.

Nitrogen- and phosphorus-rich environments can enhance the daily growth rate of seaweed **(Oliveira *et al*., 2012)**. According to **Marda *et al*. (2015)**, phosphorus can be directly utilized by seaweeds. This study revealed that the phosphorus absorption rate of *Caulerpa* sp. was higher than that of *Gracilaria* sp., with values of 0.093 mg/m²/day and 0.029 mg/m²/day, respectively. These absorption rates are higher than those reported by **Zhang *et al*. (2025)**, who found that *Caulerpa lentillifera* absorbed phosphorus at a rate of 0.073 mg L^{-1}.

Fluctuations in ammonia, nitrite, and nitrate levels in aquaculture systems occur due to interactions between nitrogen production from the excretion of cultured organisms and feed decomposition, as well as biological processes carried out by microorganisms. Nitrification is the oxidation of ammonia into nitrate by *Nitrosomonas* sp. and *Nitrobacter* sp. bacteria, whereas denitrification is the biological conversion of nitrate (NO_3^-) into nitrite (NO_2^-), nitrous oxide (N_2O), and molecular nitrogen (N_2) **(Hastuti, 2011)**. Environmental factors, such as pH, dissolved oxygen, temperature, and organism density, influence the effectiveness of these processes. **Van Rijn *et al*. (1996)** revealed that an appropriate biofilter system can control nitrogen compound fluctuations in aquaculture systems, maintaining water quality and supporting seaweed growth.

This study showed a reduction in the ammonia, nitrite, nitrate, and phosphate concentrations in the cultivation medium. At the beginning of the cultivation period, the medium had a high ammonia concentration of 0.783mg L^{-1}. This level is commonly found in shrimp aquaculture effluents, with values ranging from 0.8 to 2mg L^{-1} **(Maysabila *et al*., 2023)**. According to **Boyd (1990)**, ammonia concentrations > 0.45mg L^{-1} can inhibit shrimp growth rates by 50%; therefore, phytoremediation is necessary at a concentration of 0.783mg L^{-1}. The highest reduction in concentration was observed in the *Caulerpa* sp. medium (84.15 %), followed by *Gracilaria* sp. (74.97 %) and *K. alvarezii* (67.30 %). These results confirm that *Caulerpa* sp. has a higher ammonia absorption rate than the other treatments. **Mubarok and Zainuri (2024)** reported that *Gracilaria* sp. can reduce ammonia levels by 74.44%, whereas *K. alvarezii* can reduce ammonia levels by 42% **(Mithra *et al*. 2012)**.

Fluctuations in nitrate concentrations across treatments are suspected to be due to differences in the nitrogen absorption capabilities among seaweed species. Previous research confirmed that *Caulerpa* sp. exhibits high nitrogen absorption efficiency, reaching 100% at high salinity (35 ppt) compared to low salinity **(Sia *et al*., 2024)**. This aligns with the results of the present study, which was conducted at a salinity of 32.54–38.09 ppt, within the optimal range for nitrate absorption. Previous studies have explained that *K. alvarezii* at salinities >34 ppt experiences reduced nitrogen absorption capacity due to exceeding salinity tolerance limits **(Aris *et al*., 2021)**. Additionally, *Gracilaria* sp. showed a decrease in nitrate concentration. Suboptimal salinity inhibits growth rates, alters tissue and cell structures, and reduces stomatal size, thereby impacting nutrient absorption. **Lobban and Harrison (1994)** stated that salinity exceeding the optimal range for seaweed inhibits algal cell growth and development, showing a linear and inversely proportional (negative) relationship with salinity. This condition reduces seaweed survival capacity, making it more susceptible to viral and bacterial infections that damage the thallus **(Adharini *et al*., 2021)**.

This study confirmed fluctuations in phosphate levels in the cultivation media of *Gracilaria* sp., *K. alvarezii*, and *Caulerpa* sp. The highest reduction in phosphate concentration was observed in the *Gracilaria* sp. medium (92.2 %). According to **Komarawidjaja (2005)**, *Gracilaria* can directly absorb orthophosphate from water and accumulate it in the cells. *Gracilaria* utilizes phosphate absorption for the formation of cells. Phosphate plays a role as a biomolecule in nucleic acids, proteins, and phospholipids and functions in cell membrane formation, enabling energy distribution within cells **(Agustina, 2004)**.

The results of this study demonstrate that selecting appropriate seaweed species can enhance the effectiveness of phytoremediation in shrimp aquaculture effluents and improve the sustainability of aquaculture water quality.

CONCLUSION

This study showed that *Caulerpa* sp. has the highest daily growth, nitrogen (N), and phosphorus (P) absorption rates compared to *Gracilaria* sp. and *K. alvarezii*, making it the best candidate for bioremediating shrimp farming wastewater. Optimal environmental management, particularly in terms of salinity and water circulation, is necessary to ensure optimal seaweed growth.

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