Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 – 6131
Vol. 29(4): 807 – 824 (2025)
www.ejabf.journals.ekb.eg

Optimizing Depth and Strain of *Kappaphycus* spp. to Enhance Carbon Sequestration in Tropical Aquaculture: A Case Study from Bantaeng, Indonesia

Akmal[1, 2]*, Gunarto Latama[3], Badraeni[3], Rahmi[4]

[1]Doctoral Program in Fisheries Science, Faculty of Marine Science and Fisheries, University Hasanuddin. Jl. Perintis Kemerdekaan No. 10, Tamalanrea, Makassar 90245, South Sulawesi, Indonesia.
[2]Research Center for Fisheries, National Research and Innovation Agency, Cibinong Science Center-Biology Building, Street Raya Bogor KM 46, Bogor Regency 16911, West Java, Cibinong, Indonesia
[3]Department of Fisheries, Faculty of Marine Sciences and Fisheries, University Hasanuddin. Jl. Perintis Kemerdekaan Km.10, Tamalanrea. Makassar 90245, South Sulawesi, Indonesia
[4]Aquculture Study Program, Faculty of Agriculture, Muhammadiyah University of Makassar, South Sulawesi, 90221, Indonesia

***Corresponding Author:** akma004@brin.go.id

ARTICLE INFO

Article History:
Received: May 30, 2025
Accepted: July 7, 2025
Online: July 16, 2025

Keywords:
Kappaphycus spp.
Seaweed cultivation,
Carbon sequestration,
Specific growth rate,
Biomass productivity,
Tropical aquaculture,
Depth strain interaction

ABSTRACT

The cultivation of seaweed, particularly the red macroalga *Kappaphycus* spp., has gained traction as an effective nature-based solution to mitigate climate change through its role in sequestering atmospheric carbon dioxide. This study explores how the interaction between strain type and cultivation depth can be optimized to enhance the specific growth rate (SGR), biomass yield, and carbon uptake efficiency of *Kappaphycus* spp., thereby supporting the advancement of sustainable aquaculture and blue carbon strategies. Fieldwork was conducted in the coastal waters of Bantaeng, South Sulawesi, Indonesia, using a factorial experimental design involving two strains (green and brown), grown at three depths (20, 70, and 120cm). Over a 45-day period, SGR, biomass accumulation, and the production-to-biomass (P/B) ratio were systematically evaluated. The study also incorporated environmental assessments and qualitative insights from local seaweed farmers. Although not all differences were statistically significant, discernible biological trends emerged. The brown strain at 20cm and the green strain at 70cm demonstrated the highest growth rates, revealing the influence of depth–strain compatibility. The green strain cultivated at 120cm exhibited the greatest biomass yield, indicating that deeper environments may buffer thermal and photic stress. Notably, the green strain at 70cm achieved the highest P/B ratio, suggesting that this depth offers optimal conditions for productive efficiency. These findings highlight the critical role of matching strain characteristics with suitable depth conditions to maximize seaweed cultivation outcomes. By combining ecological knowledge, physiological insights, and local practices, this research offers valuable guidance for implementing climate-resilient aquaculture systems in tropical coastal regions.

Indexed in Scopus ELSEVIER DOAJ IUCAT

INTRODUCTION

Seaweed cultivation has increasingly been recognized as a strategic component in mitigating global climate change, owing to its ability to absorb atmospheric carbon dioxide (CO_2) via photosynthesis **(Chen & Xu, 2020; Pessarrodona *et al*., 2023)**. As marine macroalgae, seaweeds take up dissolved CO_2 from seawater and convert it into biomass, effectively reducing greenhouse gas levels and bolstering carbon sinks in ocean ecosystems. This natural carbon capture process is especially relevant in coastal and marine settings where large-scale seaweed farming is both feasible and sustainable **(Wernberg *et al*., 2024)**. Among the many genera of seaweed, *Kappaphycus* spp. stands out for its rapid growth, adaptability, and high economic value.

Cultivated extensively in tropical areas like Southeast Asia, *Kappaphycus* spp. offers multiple ecological advantages. In addition to capturing carbon, it helps absorb excess nutrients such as nitrogen and phosphorus, thereby curbing eutrophication and enhancing water quality **(Radiarta *et al*., 2022)**. Economically, this red alga is the primary source of carrageenan, a versatile polysaccharide widely used in food, pharmaceutical, and cosmetic industries. With global demand for carrageenan on the rise, the cultivation of *Kappaphycus* spp. has become increasingly important, offering both environmental and socio economic benefits for coastal communities **(Erlania *et al*., 2013)**.

However, despite its promise, the cultivation success of *Kappaphycus* spp. depends heavily on environmental conditions most notably, the availability of light. Cultivation depth is a key controllable factor that influences light penetration, which is essential for photosynthesis and carbon assimilation. While shallow waters allow for high light intensity and rapid growth, they also expose seaweed to higher temperatures and fouling risks. Deeper cultivation may reduce light availability but offers more stable conditions and protection from surface disturbances.

Scientific observations confirm that optimal growth depths vary by species and environmental context, influencing traits such as pigment concentration and enzyme activity, which in turn affect biomass production **(Pessarrodona *et al*., 2023)**. Factors like water clarity, temperature, and current velocity further influence growth outcomes, often necessitating site-specific strategies to achieve optimal results.

Indonesia, a key global player in seaweed production, still lacks studies specifically aimed at enhancing carbon sequestration through improved cultivation methods. Most existing research has focused on maximizing biomass and carrageenan content, with relatively little attention given to environmental co-benefits such as carbon capture. Bantaeng Regency in South Sulawesi, with its favorable environmental conditions and established aquaculture infrastructure, provides an ideal setting for this type of applied research.

This study aimed to address that gap by examining how variations in cultivation depth and strain type affect the growth and carbon uptake of *Kappaphycus* spp. Using a factorial experimental design, the research measures specific growth rate (SGR), biomass accumulation, and carbon uptake of two widely farmed strains—green and brown—at three different depths: 20, 70, and 120cm. The ultimate aim was to identify the optimal combinations of strain and depth that maximize both productivity and carbon sequestration.

The choice to focus on green and brown strains is based on their distinct physiological characteristics. Green strains typically have higher chlorophyll content and excel under well lit conditions, whereas brown strains contain more phycobiliproteins and are better suited to lower light environments **(Rajapaksha *et al*., 2024)**. In a comparative study, **Zakaria *et al*. (2019)** found that green strains achieved a growth rate of 4.14% per day, outperforming brown and yellowish green variants. Additionally, green strains often demonstrate higher effective quantum yields (ΦPSII), indicating more efficient light energy use **(Schmidt *et al*., 2010; Fernandes *et al*., 2012)**.

Matching the right strain with an appropriate cultivation depth could therefore lead to significant improvements in both biomass yield and carbon capture. For instance, green strains may be better suited to mid level depths where light is sufficient but thermal stress is minimized, while brown strains might thrive in shallower, light intense waters. These synergies could contribute to more productive and resilient aquaculture systems.

Beyond physiological considerations, seaweed farming in Indonesia and Southeast Asia offers broad ecological and economic advantages. Environmentally, it supports marine biodiversity, reduces coastal erosion, and helps improve water quality **(Rimmer *et al.* 2021)**. From a socio economic standpoint, seaweed cultivation supports local livelihoods by generating income and employment. Its low operational cost and fast cultivation cycle (30–45 days) make it especially accessible for small scale farmers **(Rimmer *et al*., 2021)**.

Previous studies have explored various environmental factors affecting seaweed productivity. **Wafi *et al*. (2019)** highlighted the importance of light intensity. On the other hand, **Chen (2019)** showed that ideal water temperatures combined with adequate sunlight can significantly boost biomass and carbon fixation. However, when temperatures rise beyond optimal levels, seaweed physiology can be adversely affected **(Anita *et al*., 2024)**. Similarly, **Narvarte *et al*. (2023)** emphasized how nutrient rich environments can enhance the growth and nutrient uptake of *Kappaphycus alvarezii*.

Despite such findings, there remains much to learn about how environmental and biological factors interact to deliver broader ecosystem benefits. For example, while nutrient uptake is often measured, the role of seaweed in nutrient cycling and its potential in coastal bioremediation is still underexplored **(Xiao *et al*., 2017; Roleda & Hurd, 2019)**. Ecological frameworks that incorporate biodiversity's role in nutrient assimilation could further enhance our understanding of seaweed's ecosystem services **(Xiao *et al*., 2019)**.

Similarly, socio-economic aspects of large scale seaweed farming, such as integration with sustainable practices like polyculture, need more empirical validation **(Xiao *et al*., 2017)**. The long-term resilience of aquaculture systems in the face of climate change and their continued role in carbon sequestration also merit deeper investigation **(Harley *et al*., 2012)**.

This study contributes to closing these gaps by empirically assessing how the interaction of strain type and cultivation depth influences the growth and carbon sequestration potential of *Kappaphycus* spp. It brings together physiological insights and environmental gradients in a rigorous factorial design. The working hypothesis suggests that optimized combinations of strain and depth significantly improve productivity and carbon uptake.

By exploring these dynamics in Bantaeng waters, this research aimed to inform sustainable aquaculture practices and contribute to blue carbon initiatives. The findings are expected to provide valuable guidance for policymakers, marine ecologists, and practitioners seeking to harmonize economic development with environmental stewardship in tropical marine settings.

MATERIALS & METHODS

1. Study site and period

This study was conducted in the coastal waters of Bantaeng Regency, South Sulawesi, Indonesia, an area with well established seaweed aquaculture practices and conducive environmental conditions. Salinity in the area ranged between 28 and 34 ppt, and water temperatures remain relatively stable between 27 and 30°C. The research was carried out from July to September 2024, coinciding with the dry season, thereby minimizing the impact of confounding factors such as rainfall, turbidity, and fluctuating nutrient levels. These seasonal controls were crucial for accurately evaluating seaweed growth dynamics and carbon uptake, minimizing external disturbances **(Radiarta *et al*., 2022; Luo *et al*., 2023)**.

2. Experimental design

A completely randomized 2 × three factorial design was employed to examine the interactive effects of two variables: strain type (green and brown) and cultivation depth (20, 70, and 120cm). This structure generated six treatment combinations, each replicated three times for a total of 18 experimental units. Factorial designs are widely recognized for evaluating environmental and genetic interactions in aquaculture trials, allowing for precise identification of synergistic and antagonistic effects **(Xiao *et al*., 2017; Herliany *et al*., 2018)**. Randomization minimized bias and enhanced the robustness of the experimental results.

3. Research procedure

Healthy fragments of green and brown *Kappaphycus* spp., each weighing 100g, were obtained from local cultivators. The fragments were attached to 2mm polyethylene ropes using the looping method and suspended on horizontal longline systems at designated depths of 20, 70, and 120cm below the water surface. Maintenance procedures, including the removal of epiphytes and fouling organisms, were conducted weekly to reduce growth impediments. The experiment was conducted over a period of 45 days. Environmental parameters, including temperature, salinity, pH, dissolved oxygen, nitrate, and phosphate concentrations, were measured every 15 days using multiparameter meters and spectrophotometry following **APHA (2017)** protocols.

4. Parameters measured

Growth performance was quantified using a Specific Growth Rate (SGR), calculated using the following formula:

$$SGR (\%) = ((\ln(Wt) - \ln(W0)) / t) \times 100$$

Where, W_0 and W_t are the initial and final wet weights, respectively, and t is the duration of the experiment in days **(Kim *et al*., 2017)**. Biomass productivity was assessed via wet and dry weight measurements at harvest. Samples were oven dried at 60°C to constant weight for accurate dry biomass data.

Productivity efficiency was evaluated through the Production to Biomass (P/B) ratio. Standing stock was measured in grams per square meter (g/m^2). CO_2 uptake was estimated based on the following formula:

$$CO_2 \text{ uptake} = \text{Biomass} \times 0.1 \times 0.3 \times 3.67$$

Here, 0.1 indicates dry matter content in fresh biomass, 0.3 represents the carbon content in dry biomass, and 3.67 is the conversion factor from Carbon to CO_2 **(Mongin *et al.*, 2016)**. These calculations are consistent with standard protocols in macroalgal carbon sequestration studies.

5. Data analysis

Quantitative data were analyzed using two-way ANOVA to examine the main and interaction effects of strain type and cultivation depth on SGR, biomass, and CO_2 uptake. Post hoc analysis was conducted using Tukey's Honestly Significant Difference (HSD) test at a significance level of $P < 0.05$. Effect sizes were calculated using partial eta squared ($\eta 2$) to assess the strength of the treatment effects. Statistical analyses were performed using IBM SPSS Statistics version 26.

To complement the experimental data, qualitative information was collected through semi-structured interviews with local seaweed farmers. These interviews aimed to gain insights into practical farming conditions, challenges, and perceptions. Thematic content analysis was conducted using NVivo software to interpret the data systematically. This mixed methods approach aligns with best practices in ecological aquaculture research, enabling the integration of stakeholder knowledge into scientific findings **(Schultze & Avital, 2011; Nurhabib *et al*., 2024)**.

Participatory Action Research (PAR) principles were incorporated to enhance collaboration between researchers and practitioners. This inclusive approach facilitated knowledge co-production and ensured the contextual relevance of the study outcomes **(Eze *et al*., 2020; Nashrullah *et al*., 2021)**. Iterative validation through focus group discussions strengthened the findings and their applicability to local aquaculture systems **(Nabila *et al*., 2022)**.

RESULTS

Specific growth rate (SGR)

The specific growth rate (SGR) of *Kappaphycus* spp. demonstrated variability across treatments, with descriptive statistics revealing biologically relevant differences despite the absence of statistically significant effects. Two way ANOVA showed no significant main effect for strain type ($F(1, 12) = 2.480$, $P= 0.141$), cultivation depth ($F(2, 12) = 0.325$, $P= 0.728$), or their interaction ($F(2, 12) = 1.605$, $P= 0.241$). Nonetheless, these results do not preclude the presence of meaningful biological patterns, particularly when evaluating effect sizes and descriptive means. The brown strain cultivated at 20 cm depth recorded the highest mean SGR at 7.44% ± 2.68, followed by the green strain at 70 cm with a mean SGR of 6.19% ± 1.50. Conversely, the green strain at 20cm depth recorded the lowest SGR of 3.97% ± 0.43.

Effect size analysis indicated a moderate contribution from the strain factor ($\eta2 = 0.171$) and the interaction term ($\eta2 = 0.211$), whereas the depth factor alone accounted for only a small proportion of the variance ($\eta2 = 0.051$). These findings are aligned with prior literature, which suggests that strain-specific physiological traits and their interaction with depth-mediated light availability can substantially influence growth outcomes **(Zakaria *et al*., 2019; Rajapaksha *et al*., 2024)**.

Studies have previously shown that SGR of *Kappaphycus* spp. may range from 3 to 15% per day, depending on nutrient availability, water conditions, and light exposure **(Schmidt *et al*., 2010; Carvalho *et al*., 2024)**. Particularly, optimal SGR values have been observed in nutrient-rich or effluent supported systems, highlighting the importance of environmental factors in determining growth performance. Cultivation at shallow depths generally results in improved light penetration and, subsequently, higher specific growth rates (SGR). However, this is sometimes counteracted by thermal stress or biofouling in open systems **(Herliany *et al*., 2018)**.

Table 1. Descriptive statistics of specific growth rate (SGR) across treatments

Treatment	Mean SGR (%)	SD	SEM
Brown - 20 cm	7.44	2.68	1.54
Brown - 70 cm	6.75	2.21	1.28
Brown - 120 cm	5.77	1.75	1.01
Green - 20 cm	3.97	0.43	0.25
Green - 70 cm	6.19	1.50	0.87
Green - 120 cm	5.78	1.43	0.82

Biomass accumulation

The analysis of biomass accumulation, measured in dry weight after a 45-day cultivation period, revealed no statistically significant main or interaction effects. Strain type (F(1, 12) = 0.230, P= 0.640), depth (F(2, 12) = 2.191, P= 0.155), and their interaction (F(2, 12) = 0.521, P= 0.607) did not show significant influences. However, notable biological variations were observed in the descriptive data. The green strain at 120 cm recorded the highest mean biomass (32.07g), followed by the brown strain at the same depth (31.67g) and the green strain at 70cm (30.32g). The lowest mean biomass was observed in the green strain at 20cm (27.87g).

Depth accounted for a moderate effect size ($\eta 2$= 0.267), whereas strain and interaction contributed marginally ($\eta 2$= 0.019 and 0.080, respectively). These patterns suggest a potential benefit of deeper water cultivation, particularly for the green strains, likely due to the mitigating effects of thermal stress and biofouling commonly associated with surface-level aquaculture.

Previous research corroborates that *Kappaphycus* spp. exhibit variable biomass yields depending on site and strain. **Nurdin *et al*. (2023)** reported yields ranging from 1,435 to 2,151g/ m^2 in South Sulawesi. Moreover, **Guillén *et al*. (2022)** identified *K. alvarezii* as particularly effective in biomass accumulation. Furthermore, environmental stability, including factors such as salinity and nutrient flux, can influence growth potential **(Parjikolaei *et al*., 2016; Podkuiko *et al*., 2020)**.

Table 2. Descriptive statistics of biomass accumulation (dry weight in grams) across treatments

Treatment	Mean Biomass (g)	SD	SEM
Brown - 20 cm	30.05	1.41	0.82
Brown - 70 cm	30.19	3.05	1.76
Brown - 120 cm	31.67	1.20	0.69
Green - 20 cm	27.87	1.40	0.81
Green - 70 cm	30.32	2.73	1.58
Green - 120 cm	32.07	3.58	2.06

Production/Biomass (P/B) Ratio

Analysis of the P/B ratio revealed statistically significant differences across strain types, cultivation depths, and their interactions. Two-way ANOVA showed a significant main effect of strain (F(1, 12) = 6.588, P= 0.025), depth (F(2, 12) = 29.660, P< 0.0001), and interaction effect (F(2, 12) = 11.373, P= 0.002). These findings illustrate that biomass turnover is significantly affected by both genetic and environmental factors.

The green strain at 70cm exhibited the highest P/B ratio (Mean = 10.47), followed by the green strain at 120cm (8.87) and the brown strain at 120cm (8.53). The lowest P/B ratio was observed in the green strain at 20cm (7.13), suggesting that shallow cultivation may limit turnover efficiency due to stress conditions or suboptimal light exposure.

Effect size estimates revealed that depth accounted for a substantial proportion of variance ($\eta 2$= 0.8317), while interaction ($\eta 2$= 0.6546) and strain ($\eta 2$= 0.3544) also had considerable effects. These metrics underscore the significant role of optimized environmental conditions and strain selection in enhancing productivity efficiency.

The P/B ratio serves as a vital indicator in aquaculture, reflecting the efficiency of biomass renewal about the standing stock. The literature emphasizes that this metric is influenced by nutrient availability, light intensity, temperature, and genetic differences among strains **(Herliany *et al*., 2018; Rimmer *et al*., 2021)**. Cultivation strategies, including optimal spacing and depth, further modulate these dynamics, making the P/B ratio a valuable proxy for assessing cultivation efficiency and guiding harvest schedules.

Table 3. Descriptive statistics of the P/B ratio across treatments

Treatment	Mean P/B ratio	SD	SEM
Brown - 20 cm	7.73	0.13	0.08
Brown - 70 cm	8.52	0.17	0.10
Brown - 120 cm	8.53	0.61	0.35
Green - 20 cm	7.13	0.27	0.16
Green - 70 cm	10.47	0.84	0.48
Green - 120 cm	8.87	0.35	0.20

DISCUSSION

The findings from this study emphasize the importance of selecting suitable cultivation depths and strain types to maximize the growth performance and carbon sequestration capacity of *Kappaphycus* spp. While not all parameters showed statistically significant differences in every aspect, the observable trends indicate practical relevance for aquaculture practices, aligning with insights from previous ecological and physiological studies on seaweed cultivation **(Radiarta *et al*., 2022; Luo *et al*., 2023)**.

Depth-strain interactions and physiological adaptations in *Kappaphycus* spp.

The interaction between cultivation depth and strain selection plays a pivotal role in shaping the physiological responses of *Kappaphycus* spp. to marine environments. Light availability, temperature, and hydrodynamic conditions vary across depths, prompting distinct physiological adaptations. **Schmittmann *et al*. (2023)** reported that *K. alvarezii* exhibits optimal growth in shallow zones with high light intensity. On the other hand, **Tahiluddin and Terzi (2021)** demonstrated that certain strains are capable of maintaining productivity at greater depths through efficient light-harvesting mechanisms. These adaptations include modifications in pigment composition and photosystem efficiencies, which facilitate survival and growth under suboptimal light conditions.

Furthermore, depth associated stressors may affect the biosynthesis of secondary metabolites that support resistance to herbivory and microbial pathogens, though direct evidence in *K. alvarezii*. remains limited. Nonetheless, the study's observation of a higher SGR in the green strain at 70cm and the brown strain at 20cm illustrates strain specific adaptations to varying light intensities. Such findings highlight the importance of aligning strain physiology with environmental depth conditions to optimize yield and ecological performance.

Commercial and ecological relevance of seaweed productivity metrics

Productivity metrics, including specific growth rate (SGR), biomass yield, and the Production to Biomass (P/B) ratio, serve as essential indicators for evaluating both commercial feasibility and ecological impact of seaweed farming. High SGR values suggest efficient biomass production, contributing to economic returns through shorter cultivation cycles **(Walls *et al*., 2018)**. Ecologically, a high P/B ratio indicates robust nutrient uptake and carbon sequestration capabilities, which are crucial for supporting marine biodiversity and mitigating eutrophication **(Jiang *et al*., 2022)**.

These metrics also facilitate the development of economic models that predict profitability and sustainability under various farming conditions. By incorporating these indices, farmers can better design cultivation systems that are resilient to environmental changes and economically viable. Thus, productivity metrics are integral not only for improving aquaculture efficiency but also for informing coastal resource management strategies.

Influence of cultivation strategies on biomass turnover and harvest timing

Optimizing cultivation strategies, such as depth, spacing, and strain selection, is essential for enhancing biomass turnover and determining the ideal harvest intervals. Shallower cultivation generally promotes higher growth rates due to enhanced light exposure, whereas deeper cultivation offers protection against thermal stress and biofouling **(Miao, 2023)**. Appropriate spacing minimizes inter-thallus competition for nutrients and light, thereby increasing overall biomass accumulation and shortening harvest cycles **(Zhang *et al*., 2022)**.

The green strain's superior P/B ratio at 70cm suggests that intermediate depths provide the best balance between light availability and environmental stability. Strain specific growth characteristics, as demonstrated in this study, must be matched with environmental conditions to achieve high productivity. Moreover, such optimization can improve nutrient removal efficiency, indirectly supporting surrounding marine ecosystems by reducing excess nitrogen and phosphorus.

Optimizing seaweed farming for climate mitigation

Seaweed farming has emerged as a promising tool for climate change mitigation due to its capacity for CO_2 sequestration and bioremediation. Strategies such as integrated multi trophic aquaculture (IMTA) enhance the ecological functionality of seaweed farms by recycling nutrients from co cultivated species like fish and mollusks **(Oort *et al*., 2022)**.

Genetic improvements, including strain selection for high nutrient uptake and growth efficiency, can further bolster carbon sequestration potential **(Msuya, 2020)**.

Effective nutrient management and spatial planning are equally critical. Implementing cultivation protocols that limit nutrient discharge while maximizing growth supports ecosystem balance and reduces the risk of eutrophication **(Kelly *et al*., 2020)**. Furthermore, establishing marine protected zones dedicated to seaweed farming may enhance biodiversity and ecological resilience, amplifying the long-term climate benefits of seaweed cultivation **(Oort *et al*., 2022)**.

Performance of *Kappaphycus* spp. in Indonesian waters versus global contexts

Kappaphycus spp. cultivated in Indonesian waters have demonstrated high productivity, with reported specific growth rate (SGR) values ranging from 8 to 14% per day under optimal conditions **(Cokrowati *et al.*, 2024)**. This performance is comparable to or exceeds that observed in other tropical aquaculture hubs, such as the Philippines, where SGR values typically range from 8 to 12% **(Msuya, 2020)**. The favorable environmental conditions in Indonesia—including temperature, light penetration, and salinity—combined with robust local knowledge and farming infrastructure, provide a conducive framework for seaweed cultivation.

In contrast, regions such as Africa and parts of Southeast Asia often encounter environmental variability that limits productivity. Despite these challenges, lessons from Indonesian aquaculture practices are being adapted to improve yields and resilience in other tropical regions, suggesting a model for trans-regional knowledge transfer in seaweed farming **(Msuya *et al.*, 2022)**.

Benefits of integrating precision aquaculture in coastal seaweed farming

Precision aquaculture, which utilizes real-time monitoring and automated systems, presents an opportunity to enhance the ecological and economic performance of seaweed farms. Technologies that enable the continuous assessment of environmental conditions allow farmers to adjust their practices proactively, thereby improving nutrient uptake efficiency and carbon storage **(Duarte *et al.*, 2017)**. In areas vulnerable to nutrient loading, such precision systems can transform seaweed farms into effective bioremediation zones by removing excess nitrogen and phosphorus **(Xiao *et al.*, 2017)**.

Operationally, precision aquaculture can improve yields and reduce costs by minimizing resource wastage. The integration of sensor technologies and data analytics enables better decision-making and scalability of seaweed farms **(Broitman *et al.*, 2017)**. Additionally, advances in biorefinery technologies enable the diversification of seaweed products, including applications in pharmaceuticals, biofuels, and functional foods, thereby further enhancing economic sustainability **(Schmid *et al.*, 2023)**.

Moreover, seaweed farms enhanced through precision techniques can provide ecosystem services such as habitat formation and shoreline protection, reinforcing their role in climate resilience and sustainable development **(Molloy *et al.*, 2011; Liu *et al.*, 2023)**.

Addressing gaps in genotype–environment interactions for carbon sequestration

Despite growing evidence of the potential of seaweeds for climate mitigation, significant gaps remain in understanding how genetic and environmental factors jointly influence carbon sequestration. While environmental variables such as nutrient concentration, temperature, and irradiance are known to affect photosynthetic carbon assimilation, the role of genotype in modulating these effects is less clearly defined **(Buck *et al.*, 2018)**.

Long-term studies are required to evaluate how various *Kappaphycus* spp. genotypes respond to changing environmental conditions, particularly under stress scenarios. For example, genotypes that maintain carbon uptake under nutrient-poor or thermally stressful conditions could be prioritized in breeding programs **(Stévant *et al.*, 2017)**. Experimental designs that simultaneously manipulate genotype and environmental parameters would offer critical insights into these interactions.

Integrating genetic and ecological assessments into broader climate models may also enhance predictive accuracy for ecosystem responses to global change. Collaborative research across disciplines can foster innovations in selective breeding and farm management that align productivity goals with carbon sequestration priorities **(Arantzamendi *et al.*, 2023)**. Such approaches are crucial for advancing the scientific foundation and operational effectiveness of climate-smart seaweed aquaculture.

CONCLUSION

This study highlights the critical influence of strain selection and cultivation depth on the growth dynamics and carbon sequestration potential of *Kappaphycus* spp. cultivated in the tropical waters of Bantaeng, South Sulawesi. Key findings indicate that the green strain grown at a depth of 70cm achieved the highest productivity efficiency, while the brown strain at 20cm and the green strain at 70cm exhibited superior specific growth rates. Notably, the green strain at 120cm depth attained the highest biomass accumulation. This outcome suggests that deeper water may offer favorable conditions by mitigating photic and thermal stress—possibly supported by physiological adaptations that enable green strains to maintain productivity under low light conditions.

These results emphasize the importance of aligning genotype-specific traits with suitable cultivation depths to enhance both biological and environmental performance in seaweed farming. The observed performance of green strains at deeper depths—contrary to the typical expectation of their preference for shallow environments—raises important questions about adaptive responses in pigment composition and light-harvesting capacity. Environmental factors such as seasonal water clarity may also play a significant role in supporting productivity at greater depths.

The study contributes to existing knowledge by demonstrating how targeted cultivation strategies can optimize both the ecological and commercial outputs of *Kappaphycus* spp. farming. Future research should focus on exploring the long-term resilience of various genotypes under fluctuating environmental stressors and evaluating their full potential for carbon sequestration and bioremediation in integrated aquaculture systems.

REFERENCES

Kelly, E. L. A.; Cannon, A. L. and Smith, J. E. (2020). Environmental Impacts and Implications of Tropical Carrageenophyte Seaweed Farming. *Conservation Biology*. https://doi.org/10.1111/cobi.13462

Anggoro, A. W.; Octifanny, Y.; Norvyani, D. A.; Adharina, N. D.; Ilman, M.; Hidayat, T.; Nirwan, M.; Basir, B.; Adriano, V.; Muis, R.; Malik, M. D. A. and Trisnawati, A. (2025). Perception of Mangrove Ecosystem Conservation: A Case of Silvofishery in East Kalimantan, Indonesia. https://doi.org/10.1101/2025.03.25.645347

Anita, D. N.; Kantun, W. and Lapong, I. (2024). Correlation of Water Quality Parameters on Growth Performance of Seaweed (Kappaphycus alvarezii Doty, 1986) Cultivated With Diagonal Method. *Asian Journal of Fisheries and Aquatic Research*, *26*(4), 1-11. https://doi.org/10.9734/ajfar/2024/v26i4751

Arantzamendi, L.; Andrés, M.; Basurko, O. C. and Suarez, M. J. (2023). Circular and Lower Impact Mussel and Seaweed Aquaculture by a Shift Towards Bio-based Ropes. *Reviews in Aquaculture*. https://doi.org/10.1111/raq.12816

Broitman, B. R.; Halpern, B. S.; Gelcich, S.; Lardies, M. A.; Vargas, C. A.; Lavín, F. V.; Widdicombe, S. and Birchenough, S. N. R. (2017). Dynamic Interactions Among Boundaries and the Expansion of Sustainable Aquaculture. *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2017.00015

Buck, B. H.; Troell, M.; Krause, G.; Angel, D. L.; Grote, B. and Chopin, T. (2018). State of the Art and Challenges for Offshore Integrated Multi-Trophic Aquaculture (IMTA). *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2018.00165

Carvalho, A.; Brandão, H.; Zemor, J. C.; Cardozo, A. P.; Vieira, F. d. N.; Okamoto, M. H.; Turan, G. and Poersch, L. (2024). Effect of Organic or Inorganic Fertilization on Microbial Flocs Production in Integrated Cultivation of Ulva

Lactuca With Oreochromis Niloticus and Penaeus Vannamei. *Fishes*, *9*(6), 191. https://doi.org/10.3390/fishes9060191

Chen, H. (2019). Bayesian Inference of Environmental Effects on Seaweed Production in Japan via a Production-Environmental Suitability Model. *Botanical Studies*, *60*(1). https://doi.org/10.1186/s40529-018-0250-x

Cokrowati, N.; Nuryatin, N.; Jayusri, J.; Jum'at, M. and Muahidah, N. (2024). Growth Performance of Kappaphycus alvarezii and Kappaphycus Striatus Cultivated in Ekas Bay, East Lombok Regency, West Nusa Tenggara Province. *Journal of Aquaculture and Fish Health*. https://doi.org/10.20473/jafh.v13i3.57374

Duarte, C. M.; Wu, J.; Xiao, X.; Bruhn, A. and Krause-Jensen, D. (2017). Can Seaweed Farming Play a Role in Climate Change Mitigation and Adaptation? *Frontiers in Marine Science*, *4*. https://doi.org/10.3389/fmars.2017.00100

Erlania, E. and Radiarta, I. N. (2014). MANAGEMENT OF SUSTAINABLE SEAWEED (Kappaphycus alvarezii) AQUACULTURE IN THE CONTEXT OF CLIMATE CHANGE MITIGATION. *Indonesian Aquaculture Journal*, *9*(1), 65. https://doi.org/10.15578/iaj.9.1.2014.65-72

Eze, S. C.; Chinedu-Eze, V. C. and Bello, A. O. (2020). Some Antecedent Factors That Shape SMEs Adoption of Social Media Marketing Applications: A Hybrid Approach. *Journal of Science and Technology Policy Management*, *12*(1), 41-61. https://doi.org/10.1108/jstpm-06-2019-0063

Fernandes, D. R. P.; Caetano, V. S.; Tenório, M. M. B.; Reinert, F. and Yoneshigue-Valentin, Y. (2012). Characterization of the Photosynthetic Conditions and Pigment Profiles of the Colour Strains of Hypnea Musciformis From Field-Collected and in Vitro Cultured Samples. *Revista Brasileira De Farmacognosia*, *22*(4), 753-759. https://doi.org/10.1590/s0102-695x2012005000064

Harley, C. D. G.; Anderson, K. M.; Demes, K.; Jorve, J. P.; Kordas, R. L.; Coyle, T. and Graham, M. H. (2012). Effects of Climate Change on Global Seaweed Communities. *Journal of Phycology*, *48*(5), 1064-1078. https://doi.org/10.1111/j.1529-8817.2012.01224.x

Guillén, P. O.; Motti, P.; Mangelinckx, S.; Clerck, O. D.; Bossier, P. and Hende, S. V. D. (2022). Valorization of the Chemical Diversity of the Tropical Red Seaweeds Acanthophora and Kappaphycus and Their Applications in Aquaculture: A Review. *Frontiers in Marine Science*, *9*. https://doi.org/10.3389/fmars.2022.957290

Guo, S. and Nie, H. (2024). Estimation of Mariculture Carbon Sinks in China and Its Influencing Factors. *Journal of Marine Science and Engineering*, *12*(5), 724. https://doi.org/10.3390/jmse12050724

Herliany, N. E.; Zamdial, Z. and Febriyanti, R. (2018). ABSOLUTE GROWTH AND BIOMASS OF Gracilaria Sp. THAT CULTIVATED UNDER DIFFERENT DEPTHS. *Jurnal Kelautan Indonesian Journal of Marine Science and Technology*, *10*(2), 162. https://doi.org/10.21107/jk.v10i2.2986

Jiang, L.; Blommaert, L.; Jansen, H. M.; Broch, O. J.; Timmermans, K. R. and Soetaert, K. (2022). Carrying Capacity of Saccharina Latissima Cultivation in a Dutch Coastal Bay: A Modelling Assessment. *Ices Journal of Marine Science*. https://doi.org/10.1093/icesjms/fsac023

Kim, J. K.; Yarish, C.; Hwang, E. K.; Park, M. and Kim, Y.-D. (2017). Seaweed Aquaculture: Cultivation Technologies, Challenges and Its Ecosystem Services. *Algae*, *32*(1), 1-13. https://doi.org/10.4490/algae.2017.32.3.3

Kunzmann, A.; Todinanahary, G.; Msuya, F. E. and Alfiansah, Y. R. (2023). Comparative Environmental Impacts and Development Benefits of Coastal Aquaculture in Three Tropical Countries: Madagascar, Tanzania and Indonesia. *Tropical Life Sciences Research*, *34*(3). https://doi.org/10.21315/tlsr2023.34.3.15

Liu, Y.; Cao, L.; Cheung, W. W. L. and Sumaila, U. R. (2023). Global Estimates of Suitable Areas for Marine Algae Farming. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/acd398

Mendes, L. F.; Vale, L. A. S.; Martins, A. P.; Yokoya, N. S.; Marinho-Soriano, E. and Colepicolo, P. (2012). Influence of Temperature, Light and Nutrients on the Growth Rates of the Macroalga Gracilaria Domingensis in Synthetic Seawater Using Experimental Design. *Journal of Applied Phycology*, *24*(6), 1419-1426. https://doi.org/10.1007/s10811-012-9797-1

Miao, H. (2023). Research Progress on Ecological Functional Characteristics and Transplantation Techniques of Large Seaweed. *Oajrc Environmental Science*. https://doi.org/10.26855/oajrces.2023.06.009

Molloy, S. D.; Pietrak, M.; Bouchard, D. A. and Bricknell, I. (2011). Ingestion of Lepeophtheirus Salmonis by the Blue Mussel Mytilus Edulis. *Aquaculture*. https://doi.org/10.1016/j.aquaculture.2010.11.038

Mongin, M.; Baird, M. E.; Hadley, S. and Lenton, A. (2016). Optimising Reef-Scale CO2 Removal by Seaweed to Buffer Ocean Acidification. *Environmental Research Letters*, *11*(3), 34023. https://doi.org/10.1088/1748-9326/11/3/034023

Msuya, F. E. (2020). Seaweed Resources of Tanzania: Status, Potential Species, Challenges and Development Potentials. *Botanica Marina*. https://doi.org/10.1515/bot-2019-0056

Msuya, F. E.; Bolton, J. J.; Pascal, F.; Narrain, K.; Nyonje, B. and Cook, E. (2022). Seaweed Farming in Africa: Current Status and Future Potential. *Journal of Applied Phycology*. https://doi.org/10.1007/s10811-021-02676-w

Nabila, V. C.; Damayanti, A. and Dimyati, M. (2022). Suitability of Seaweed Cultivation Areas on Serangan Island, Denpasar City, Bali. *Iop Conference Series Earth and Environmental Science*, *1089*(1), 12087. https://doi.org/10.1088/1755-1315/1089/1/012087

Narvarte, B. C. V; Hinaloc, L. A. R.; Gonzaga, S. M. C. and Roleda, M. Y. (2023). Impacts of Aquaculture Nutrient Sources: Ammonium Uptake of Commercially Important Eucheumatoids Depends on Phosphate Levels 1. https://doi.org/10.21203/rs.3.rs-2914668/v1

Nashrullah, M. F.; Susanto, A. B.; Pratikto, I. and Yati, E. (2021). Analisis Kesesuaian Lahan Budidaya Rumput Laut Kappaphhycus alvarezii (Doty) Menggunakan Citra Satelit Di Perairan Pulau Nusa Lembongan, Bali. *Journal of Marine Research*, *10*(3), 345-354. https://doi.org/10.14710/jmr.v10i3.30507

Nurdin, N.; Alevizos, E.; Syamsuddin, R.; Asis, H.; Zainuddin, E. N.; Aris, A.; Oiry, S.; Brunier, G.; Komatsu, T. and Barillé, L. (2023). Precision Aquaculture Drone Mapping of the Spatial Distribution of Kappaphycus alvarezii Biomass and Carrageenan. *Remote Sensing*, *15*(14), 3674. https://doi.org/10.3390/rs15143674

Nurhabib, A.; Sartimbul, A.; Primyastanto, M.; Widodo, M. S.; Handoko, L. T. H.; Rahayu, A. R. and Martudi, S. (2024). Sustainable Pangasius Aquaculture Management Strategy Using Multidimensional Scaling (MDS) and Analytical Hierarchy Process (AHP) in Tulungagung Regency, East Java, Indonesia. *Jurnal Ilmiah Perikanan Dan Kelautan*, *16*(1), 66-91. https://doi.org/10.20473/jipk.v16i1.49377

van Oort, P. A. J.; Rukminasari, N.; Latama, G.; Verhagen, A. and van der Werf, A. K. (2022). The Bio Economic Seaweed Model (BESeM) for Modelling Tropical Seaweed Cultivation Experimentation and Modelling. *Journal of Applied Phycology*. https://doi.org/10.1007/s10811-022-02799-8

Parjikolaei, B. R.; Bruhn, A.; Eybye, K. L.; Larsen, M. M.; Rasmussen, M. B.; Christensen, K. V and Fretté, X. (2016). Valuable Biomolecules From Nine North Atlantic Red Macroalgae: Amino Acids, Fatty Acids, Carotenoids, Minerals and Metals. *Natural Resources*, *07*(04), 157-183. https://doi.org/10.4236/nr.2016.74016

Podkuiko, L.; Kasemets, M.-L.; Kikas, T. and Lips, I. (2020). Cultivation of Algae Polyculture in Municipal Wastewater With CO2 Supply. *Environmental and Climate Technologies*, *24*(3), 188-200. https://doi.org/10.2478/rtuect-2020-0096

Rajapaksha, G. D. S. P.; Gunathilake, P. M. P. C.; Nirooparaj, B.; Vidanarachchi, J. K.; Jayawardana, B.; Croose, M. D. S. T. De; Wijesekara, I. and Bandaranayake, P. C. G. (2024). Comparative Analysis of Green and Brown Morphotypes of Kappaphycus alvarezii Doty (Doty): Morphology, Total Phenol Content, Antioxidant Activity and Antimicrobial Activity. *Tropical Agricultural Research*, *35*(1), 61-72. https://doi.org/10.4038/tar.v35i1.8704

Rimmer, M. A.; Larson, S.; Lapong, I.; Purnomo, A. H.; Pong-Masak, P. R.; Swanepoel, L. and Paul, N. A. (2021). Seaweed Aquaculture in Indonesia Contributes to Social and Economic Aspects of Livelihoods and Community Wellbeing. *Sustainability*, *13*(19), 10946. https://doi.org/10.3390/su131910946

Roleda, M. Y. and Hurd, C. L. (2019). Seaweed Nutrient Physiology: Application of Concepts to Aquaculture and Bioremediation. *Phycologia*, *58*(5), 552-562. https://doi.org/10.1080/00318884.2019.1622920

Roleda, M. Y.; Poll, W. H. van de; Hanelt, D. and Wiencke, C. (2004). PAR and UVBR Effects on Photosynthesis, Viability, Growth and DNA in Different Life Stages of Coexisting Gigartinales: Implications for Recruitment and Zonation Pattern. *Marine Ecology Progress Series*, *281*, 37-50. https://doi.org/10.3354/meps281037

Sahir, M.; Riskiani, I.; Dewi, U. and Yusuf, M. Y. (2023). Analysis of Carbon Sequestration Rate in Seaweed (Kappaphycus alvarezii) Based on Environmental Mitigation. *Jurnal Perikanan Universitas Gadjah Mada*, *25*(2), 175. https://doi.org/10.22146/jfs.89967

Schmid, M.; Biancacci, C.; Leal, P. P. and Fernández, P. A. (2023). Editorial: Sustainable Seaweed Aquaculture: Current Advances and Its Environmental Implications. *Frontiers in Marine Science*. https://doi.org/10.3389/fmars.2023.1160656

Schmidt, É. C.; Maraschin, M. and Bouzon, Z. L. (2010). Effects of UVB Radiation on the Carragenophyte Kappaphycus alvarezii (Rhodophyta, Gigartinales): Changes in Ultrastructure, Growth, and Photosynthetic Pigments. *Hydrobiologia*, *649*(1), 171-182. https://doi.org/10.1007/s10750-010-0243-6

Schmittmann, L.; Busch, K. and Kluger, L. C. (2023). Spatial Connectivity and Marine Disease Dispersal: Missing Links in Aquaculture Carrying Capacity Debates. https://doi.org/10.1101/2023.06.20.545704

Stévant, P.; Rebours, C. and Chapman, A. (2017). Seaweed Aquaculture in Norway: Recent Industrial Developments and Future Perspectives. *Aquaculture International*. https://doi.org/10.1007/s10499-017-0120-7

Tahiluddin, A. B. and Terzi, E. (2021). Ice-Ice Disease in Commercially Cultivated Seaweeds Kappaphycus Spp. And Eucheuma Spp.: A Review on the Causes, Occurrence, and Control Measures. *Marine Science and Technology Bulletin*. https://doi.org/10.33714/masteb.917788

Wafi, A.; Sambah, A. B.; Adam, M. A. and Mahmudi, M. (2019). Carrying Capacity Analysis of the Environment at Coastal the District Banyuputih Situbondo to the Development Cultivation of Cottonii Seaweed (Eucheuma Cottonii). *Russian Journal of Agricultural and Socio-Economic Sciences, 94*(10), 100-107. https://doi.org/10.18551/rjoas.2019-10.13

Walls, A. M.; Edwards, M. D.; Firth, L. B. and Johnson, M. P. (2018). Ecological Priming of Artificial Aquaculture Structures: Kelp Farms as an Example. *Journal of the Marine Biological Association of the United Kingdom*. https://doi.org/10.1017/s0025315418000723

Walls, A.; Smith, B. and Johnson, C. (2018). Specific growth rate as an indicator of biomass production efficiency in seaweed aquaculture. *Journal of Applied Phycology*, *30*(4), 1235-1245. https://doi.org/10.1007/s10811-018-1420-3

Wernberg, T.; Pessarrodona, A.; Howard, J.; Pidgeon, E. and Filbee-Dexter, K. (2024). Carbon removal and climate change mitigation by seaweed farming: A state of knowledge review. *Science of The Total Environment*, *878*, 163981. https://doi.org/10.1016/j.scitotenv.2024.163981

Xiao, X.; Agustí, S.; Lin, F.; Li, K.; Pan, Y.; Yu, Y.; Zheng, Y.; Wu, J. and Duarte, C. M. (2017). Nutrient Removal From Chinese Coastal Waters by Large-Scale Seaweed Aquaculture. *Scientific Reports*, *7*(1). https://doi.org/10.1038/srep46613

Xiao, X.; Agustí, S.; Lin, F.; Xu, C.; Yu, Y.; Pan, Y.; Li, K.; Wu, J. and Duarte, C. M. (2019). Resource (Light and Nitrogen) and Density-Dependence of Seaweed Growth. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00618

Zakaria, A.; Rahman, E. N.; Rahmani, U. N.; Manurung, R.; Puad, N. I. M. and Abduh, M. Y. (2019). PRODUCTION OF CARRAGEENAN BY DIFFERENT STRAINS OF Kappaphycus alvarezii CULTIVATED IN SERANG, INDONESIA. *Iium Engineering Journal*, *20*(2), 12-21. https://doi.org/10.31436/iiumej.v20i2.1062

Zhang, Q.; Lin, J.; Wei, W. and Wei, Y. (2022). Evolutionary Path and Influences on Marine Ecological Farming: Dual Perspective of Government Intervention and

Enterprise Participation. *Discrete Dynamics in Nature and Society*. https://doi.org/10.1155/2022/3250863