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Growth Dynamics and Carbon Content During Red Seaweed Cultivation

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ABSTRACT

The cultivation of *Kappaphycus alvarezii*, a commercially valuable red macroalga, is increasingly recognized as a cornerstone of sustainable aquaculture and blue carbon strategies, especially in tropical coastal regions like South Sulawesi, Indonesia. This study aimed to evaluate the effects of three planting densities (25g/tie, 50g/tie, 75g/tie) on biomass yield, specific growth rate (SGR), and carbon content in *K. alvarezii*, with a focus on region-specific cultivation practices in South Sulawesi. Using a completely randomized design and triplicate replications, the study tracked temporal changes across a full 45-day cycle, providing high-resolution insights into growth and carbon dynamics. Biomass yield increased over time across all treatments, with the highest final yield recorded at the 75g/tie density. However, the 50g/tie medium-density treatment achieved the highest SGR throughout the cultivation cycle and maintained stable carbon content, reflecting superior physiological performance. The 25g/tie treatment initially showed high carbon content but underperformed in overall productivity. Statistical analysis confirmed that medium density optimized both growth efficiency and biochemical composition, minimizing the stress effects observed in high-density treatments. The results suggest that medium-density planting offers an optimal balance between resource use, physiological stability, and carbon sequestration—an integrative approach not widely reported in prior regional studies. These findings support the development of climate-smart aquaculture systems and provide actionable guidance for seaweed farmers and policymakers. Optimizing planting density is therefore essential not only for improving productivity but also for enhancing the ecological sustainability of marine farming systems.

INTRODUCTION

Sustainable aquaculture has gained global relevance as a means of enhancing food security, economic resilience, and environmental health. Among its components, seaweed farming—especially of red macroalgae like *Kappaphycus alvarezii*—offers climate mitigation benefits through blue carbon pathways, biodiversity support, and nutrient cycling. These contributions situate seaweed aquaculture as both an ecological and socioeconomic asset **(Mashoreng *et al.*, 2019; Montúfar-Romero *et al.*, 2023)**. The commercial success of *K. alvarezii*, primarily valued for its carrageenan content, has significantly benefitted coastal economies in Southeast Asia. Indonesia and the Philippines, contributing over 25% of global supply, have leveraged its cultivation to drive economic diversification and food security **(Domínguez-May *et al.*, 2015; Valderrama *et al.*, 2015; Nurdin *et al.*, 2023)**. Despite its advantages, *K. alvarezii* cultivation must carefully manage planting density, a key factor that influences biomass yield, SGR, and environmental performance. Excessive density causes intra-specific competition, while sparse planting wastes cultivation space—both reducing overall productivity **(Marroig & Reis, 2010; Mulyaningrum *et al.*, 2019)**.

To address these challenges, integrated multi-trophic aquaculture (IMTA) systems have been proposed as a sustainable solution. IMTA systems combine the cultivation of various aquatic species in a synergistic arrangement, where waste nutrients from one species serve as inputs for another. In the case of *K. alvarezii*, such systems enhance nutrient uptake, improve water quality, and stabilize the ecological footprint of aquaculture operations **(Rahayu *et al.*, 2021; Heriansah *et al.*, 2022)**. However, the success of IMTA systems and other sustainable practices also hinges on the optimization of planting density, which remains a nuanced and site-specific variable.

Several studies have documented the capacity of *K. alvarezii* to absorb excess nutrients, particularly nitrogen and phosphorus, from aquaculture effluents. This ability makes it an effective biological filter that not only improves water quality but also reduces the risk of eutrophication in coastal ecosystems **(Martino *et al.*, 2021; Heriansah, 2025)**. Moreover, its cultivation contributes to the provisioning of habitat for various marine organisms, thereby enhancing local biodiversity and ecosystem resilience. Through its dual ecological and economic functions, *K. alvarezii* exemplifies the potential of climate-smart aquaculture practices.

Current research on climate-smart aquaculture underscores the importance of macroalgae cultivation in enhancing carbon sequestration. By capturing carbon in organic biomass, *K. alvarezii* contributes to the long-term storage of carbon in marine environments, which is vital for mitigating the impacts of climate change. Integrative practices that incorporate seaweed farming within broader aquaculture systems, such as IMTA, maximize resource efficiency and improve the sustainability of marine production systems **(Heriansah *et al.*, 2022; Montúfar-Romero *et al.*, 2023)**.

Despite these advancements, the influence of planting density on the physiological performance of *K. alvarezii* continues to be an area of active inquiry. Optimal planting densities are essential to ensure sufficient light penetration, nutrient availability, and water flow, all of which affect photosynthetic efficiency and growth rate. Studies have shown that excessive planting density can lead to shading and self-competition, ultimately compromising biomass yield and carrageenan quality **(Terada *et al.*, 2015; Ventura *et al.*, 2020; Aslan *et al.*, 2024)**. Conversely, strategic spacing and density optimization can enhance photosynthetic performance and overall cultivation outcomes **(Bindu & Levine, 2010; Febriyanti *et al.*, 2019)**.

In light of these observations, this study investigateD the site-specific effects of three planting densities (25g/tie, 50g/tie, 75g/tie) on biomass yield, SGR, and carbon content in *K. alvarezii*, under real-world field conditions in South Sulawesi, Indonesia—an ecologically significant but understudied region. This study's novelty lies in its integrative approach—linking density-dependent growth performance and carbon dynamics within a localized, full-cycle cultivation trial. By aligning agronomic efficiency with carbon sequestration goals, it contributes new evidence to the climate-smart aquaculture discourse, especially for Indonesia’s seaweed sector.

MATERIALS AND METHODS

Study location

This research was conducted in Mattirobaji Village, Takalar Regency, South Sulawesi, Indonesia—a region with established seaweed farming practices. The site, characterized by sandy-mud substrate and coral reef proximity, offers ideal conditions for *K. alvarezii*. Environmental parameters monitored throughout were: sea temperatures ranged from 28–30°C, salinity remained at 32–34ppt, and light intensity fluctuated between 1,500 and 2,500 lux—all within ranges conducive to photosynthetic efficiency and metabolic performance in red macroalgae **(Araújo *et al.*, 2014; Mandal *et al.*, 2014; Zhang *et al.*, 2024)**.

The site was selected based on three primary criteria. First, the area demonstrates minimal wave disturbance, providing a relatively stable aquatic environment essential for maintaining structural integrity in floating raft systems. Second, it offers a convenient accessibility for ongoing maintenance and data collection, thus facilitating regular monitoring. Third, the location has a history of successful seaweed cultivation, enhancing the reliability of the outcomes by minimizing uncertainties associated with novel environments.

Experimental design

The experiment used a completely randomized design (CRD) with three planting densities—25g/tie (low), 50g/tie (medium), and 75g/tie (high)—each replicated three times (nine units total). This triplicate setup supports internal validity and robust treatment comparisons **(Febriyanti *et al.*, 2019)**. The study focused exclusively on monoculture conditions, and future work may include multi-trophic systems to evaluate broader ecological interactions.

Seaweed cultivation was carried out using a floating raft system constructed with polyethylene ropes. This system is recognized for facilitating effective water circulation and nutrient exchange, which are pivotal for macroalgae growth **(Suryati *et al.*, 2021)**. Seaweed thalli were attached to ropes at 25cm intervals, with each raft placed 1 meter apart to minimize overlap and shading among units. Such spacing is critical to reducing self-shading, a phenomenon that can significantly hinder light penetration and lower photosynthetic efficiency **(Ventura *et al.*, 2020)**. The entire cultivation cycle spanned 45 days, with biomass harvested at intervals of Day 15, Day 30, and Day 45 to capture growth dynamics across time.

Data collection

Three parameters were tracked: biomass yield, specific growth rate (SGR), and carbon content. Biomass was measured fresh at each interval and later standardized via sun-drying (3 days) and oven-drying at 60°C for 24 hours. This conversion ensured consistency across treatments. While biomass metrics were emphasized, future studies should also include carrageenan quality and nutrient uptake for commercial insight.

To analyze carbon content, dried seaweed samples were pulverized using a mechanical mill to achieve uniform particle size. The carbon percentage was then quantified using a CHN (Carbon-Hydrogen-Nitrogen) elemental analyzer. This analytical technique involves combusting the sample in a controlled environment, capturing the resulting gases, and measuring the elemental composition. The CHN analyzer method is widely adopted for macroalgae studies due to its precision and reliability in determining the carbon sequestration potential of biomass **(Yong *et al.*, 2014; Mashoreng *et al.*, 2019)**. By quantifying carbon content, the study assessed not only the quality of the seaweed biomass but also its potential contribution to blue carbon strategies. Specific Growth Rate (SGR) was calculated using Eq. 1.

$$SGR = \frac{[\ln(Wt) - \ln(W0)]}{t} \times 100\% \qquad (1)$$

Where, Wt represents the final weight; W0 the initial weight; and t the duration in days. Measurements for SGR were taken on days 10, 15, and 20. The choice of these time points allowed the researchers to track early and mid-stage growth responses under different planting densities. Importantly, all growth measurements and environmental observations were conducted under similar weather and tidal conditions to minimize variability and ensure the accuracy of the comparative analysis.

Statistical analysis

To assess differences among planting densities, a one-way ANOVA was applied to biomass yield, SGR, and carbon content data. Tukey's HSD test followed for *post-hoc* pairwise comparisons. All analyses were performed with 95% confidence (P< 0.05). While statistically robust, the analysis reflects only short-term trends (45 days); future studies should expand to seasonal cycles for long-term validation.

The level of significance for all statistical tests was set at 95% confidence (P< 0.05), in line with conventional scientific standards. Data processing and statistical analysis were performed using advanced software platforms such as SPSS or R, both of which are widely recognized for their capability in handling complex datasets and providing reproducible results.

This rigorous methodological framework supports reliable evaluation of how planting density influences *K. alvarezii* growth and carbon potential. However, the 45-day monoculture trial offers only partial insight into long-term and integrated aquaculture systems, which warrant further investigation.

RESULTS

Biomass yield

The results of the biomass yield assessment revealed a time-dependent increase in biomass across all planting densities, with clear distinctions emerging as cultivation progressed. On Day 15, the medium planting density of 50g/tie yielded 189.02 g/tie, outperforming both the low density (25g/tie, 177.64 g/tie) and the high density (75g/tie, 172.51 g/tie). By Day 30, the 50g/tie treatment continued to show superior growth (222.37 g/tie), followed by the 25g (208.98 g/tie) and 75g (202.95 g/tie) treatments. On Day 45, however, the highest biomass yield was recorded in the high-density group, with 338.90 g/tie, while the medium and low densities produced 268.89 g/tie and 226.91 g/tie, respectively (Fig. 1).

Although the 75g/tie density achieved the highest final biomass, its slower early-stage growth suggests stress from self-shading and nutrient competition. In contrast, the 50g/tie treatment exhibited consistent growth across all time points, confirming the efficiency of moderate spacing. These outcomes align with prior studies showing that intermediate densities optimize nutrient use while minimizing physiological stress **(Hayashi *et al.*, 2007; Wenno *et al.*, 2018; Zakaria *et al.*, 2019)**.

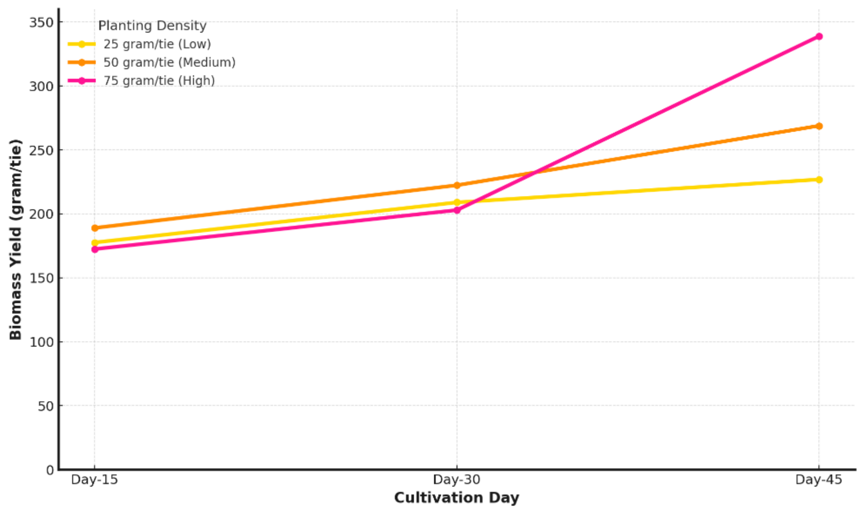

Fig. 1. Biomass planting and yield during planting cycle

Specific growth rate (SGR)

The specific growth rate (SGR) was evaluated at three time points: Days 10, 15, and 20. At each interval, the 50g/tie medium-density treatment consistently demonstrated the highest SGR, peaking at 10.6%/day on Day 15 and maintaining an elevated rate of 10.23%/day on Day 20. In contrast, the 25g/tie group showed modest growth across all intervals (5.89%, 6.93%, and 6.95%/day), while the 75g/tie group had the lowest initial rate (5.26% on Day 10), gradually increasing to 8.53%/day by Day 20 (Fig. 2).

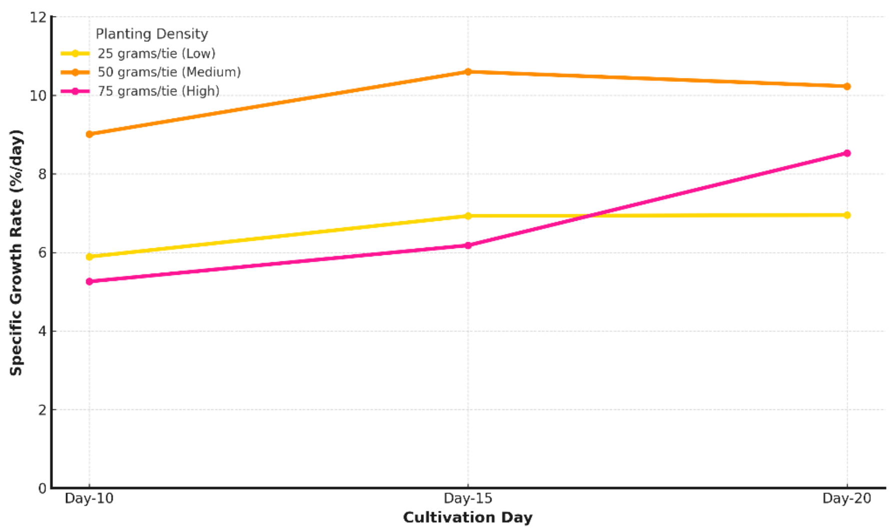

Fig. 2. Specific growth rate

These results confirm that moderate planting density supports optimal physiological performance in *K. alvarezii*. The elevated SGR observed in the 50g treatment can be attributed to a favorable balance of light exposure, nutrient availability, and spatial efficiency. Conversely, the low SGR in the 75g group during early stages aligns with the anticipated effects of self-shading and nutrient competition, which impair photosynthetic performance and energy assimilation **(Nainggolan *et al.*, 2022)**.

Dense cultures experience physiological stress, including reduced chlorophyll content and diversion of energy toward protective responses. Moderate planting, on the other hand, promotes optimal light availability and efficient nutrient uptake, supporting balanced energy use and growth **(Breanita *et al.*, 2020)**.

Carbon content

The carbon content (%C) of *K. alvarezii* biomass was also evaluated over time to assess carbon sequestration potential across planting densities. On Day 15, the highest carbon content was observed in the 25g treatment (20.08%), followed by the 75g (19.69%) and 50g (19.45%) groups. By Day 30, carbon percentages began to decline across all treatments, with the 25g, 50g, and 75g densities yielding 18.8%, 18.83%, and 18.26%, respectively. On Day 45, the downward trend persisted, with final carbon content values recorded at 17.52% (25g/tie), 18.21% (50g/tie), and 16.93% (75g/tie) (Fig. 3).

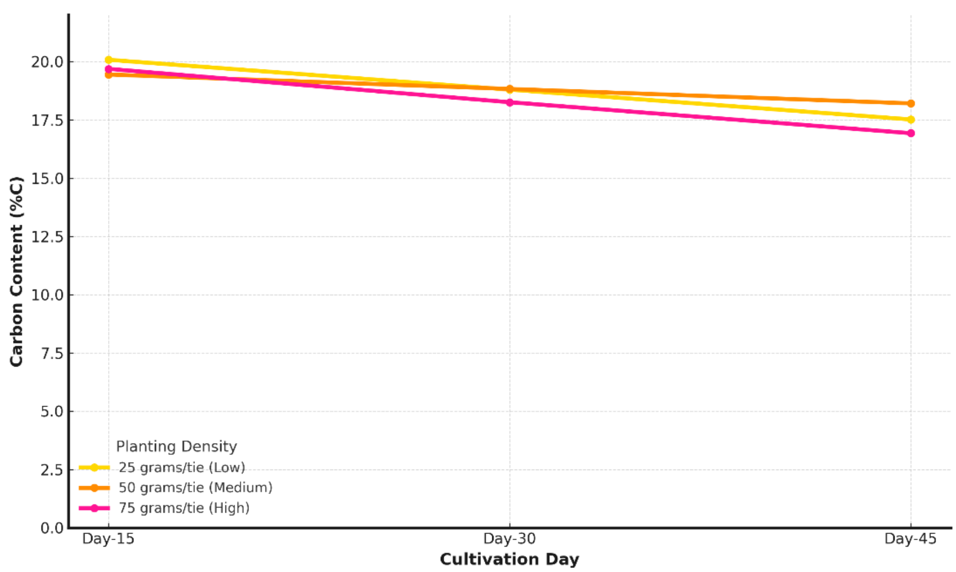

Fig. 3. Carbon content as function of cultivation time

The initial advantage in carbon content observed in the 25g treatment diminished over time, highlighting the trade-off between initial carbon accumulation and long-term biomass yield. Interestingly, the 50g treatment maintained relatively stable carbon levels while also delivering high biomass output, suggesting that moderate densities support both growth and consistent carbon sequestration. These results are consistent with findings by **Fakhraini *et al.* (2020)**, who emphasized that moderate planting densities optimize photosynthetic carbon fixation by minimizing shading and maximizing light use efficiency.

Carbon content declined over time as thalli matured and energy shifted to structural maintenance. While 25g/tie had the highest early carbon levels, the 50g/tie treatment maintained greater stability while delivering higher overall biomass—an optimal trade-off for carbon sequestration and yield **(Byers *et al.*, 1978; Fakhraini *et al.*, 2020)**.

Statistical summary

A statistical summary of all key parameters measured on Day 45 revealed notable distinctions across planting densities (Fig. 4). Biomass yield at 75g density was the highest (338.90 ± 4.15g), followed by 50g (268.89 ± 5.32g), and 25g (226.91 ± 4.21g). In terms of SGR, the 50g density achieved the highest rate (10.60 ± 0.91%/day), outperforming both the 75g (8.53 ± 0.76%/day) and 25g (6.93 ± 0.52%/day) treatments. The highest carbon content was observed in the 50g density (18.80 ± 0.28%), followed by the 75g (18.21 ± 0.45%) and 25g (17.52 ± 0.52%) treatments.

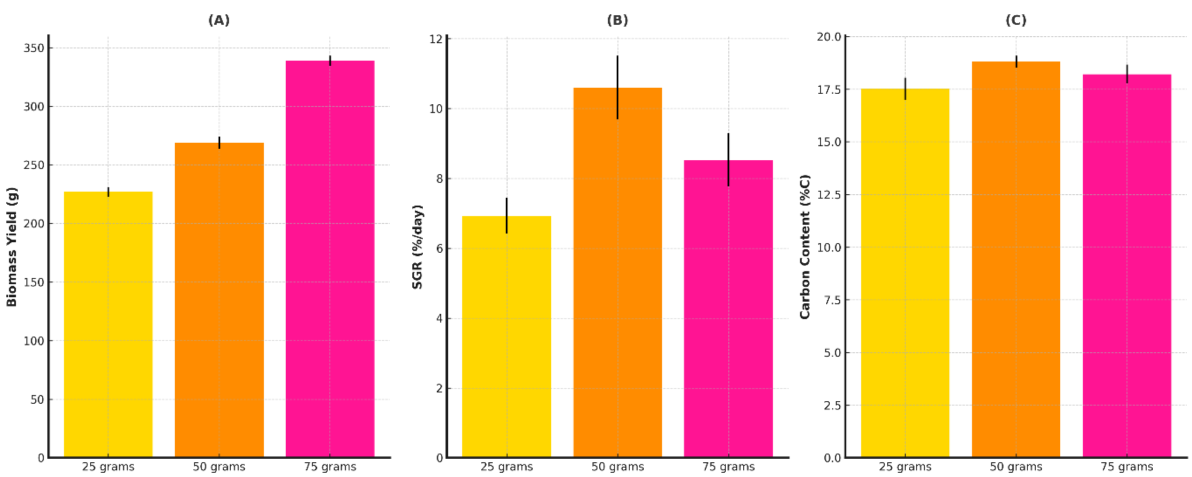

Fig. 4. Statistical summary (Mean ± SD) after 45 days

These findings confirm that the 50g/tie density offers the best balance of yield, growth rate, and carbon performance. While 75g/tie produced the most biomass, it did so with a reduced physiological efficiency, and the 25g/tie density underutilized space. The 50g/tie treatment thus demonstrates superior all-around sustainability. These findings support site-specific calibration of planting density as a vital step in maximizing ecological function and yield. Future cultivation strategies can benefit from incorporating such density data to enhance both productivity and carbon outcomes.

DISCUSSION

Biomass yield vs density

The observed relationship between biomass yield and planting density aligns with previous findings on resource competition and utilization efficiency. Although the 75g/tie treatment produced the highest final biomass, it lagged behind the 50g/tie group early in the cycle—likely due to self-shading and nutrient competition, consistent with **Kerrison *et al.* (2020)**.

Maximum biomass does not equate to optimal physiological conditions. While high density can increase absolute yield, it also induces stress, reducing efficiency and health **(Arenas *et al.*, 2002)**. The 50g/tie treatment showed consistent biomass accumulation, a valuable trait for commercial predictability **(Hayashi *et al.*, 2007; Zakaria *et al.*, 2019)**.

Growth dynamics

Specific growth rate (SGR) trends support that 50g/tie promotes an optimal metabolic state. At moderate densities, reduced self-shading and efficient nutrient access enhance photosynthesis and energy assimilation **(Nainggolan *et al.*, 2022)**. The 75g/tie group showed delayed growth, likely due to early-stage stress. Although some adaptation may have occurred, crowding still constrained energy use, mirroring compensatory morphological responses in stressed seaweed systems **(Arenas *et al.*, 2002)**. These results affirm that growth is governed not just by nutrients, but by light distribution and spacing. Balanced exposure in the 50g/tie treatment sustained high photosynthetic efficiency, enabling both early and long-term growth.

Carbon sequestration

The carbon content data further substantiate the critical role of planting density in regulating physiological efficiency and biochemical composition. Initially, the highest carbon concentration was found in the 25g/tie treatment, reflecting lower intra-thallus competition and better access to light and nutrients. This advantage, however, diminished over time as the total biomass accumulation in the 25g/tie group plateaued, leading to a reduced contribution to overall carbon sequestration potential.

Middelboe and Binzer (2004) and **Richards *et al.* (2011)** have discussed the trade-offs inherent in densely planted systems, where increased biomass does not necessarily translate to higher carbon concentrations due to metabolic stress. In the present study, the 75g/tie treatment, although yielding the highest biomass, recorded the lowest final carbon content. This outcome is indicative of stress-induced shifts in metabolic priorities, where energy is diverted from carbon assimilation toward maintenance and protective mechanisms such as antioxidant synthesis and pigment adjustments.

The 50g/tie density yielded the most stable carbon content while maintaining high biomass, making it well-suited for climate-smart aquaculture that integrates growth and sequestration outcomes **(Lai *et al.*, 2022; Lian *et al.*, 2023)**.

The role of planting density in modulating carbon sequestration is further illustrated by the interplay between structural and biochemical development in *K. alvarezii*. In early growth phases, lower densities promote rapid cell division and carbon-rich compound synthesis due to minimal resource competition. However, over time, such systems underutilize the available cultivation area, limiting their total sequestration potential. Conversely, overly dense systems compromise individual thallus health, reducing the carbon content per unit biomass **(Johnston *et al.*, 2023)**.

Sustainability implications

Combining performance and ecological metrics, the 50g/tie density emerges as the most sustainable configuration tested. It offers high SGR, carbon stability, and consistent biomass—key factors in environmentally sound aquaculture.

From a sustainability perspective, the optimization of planting density is central to advancing climate-smart aquaculture. As noted by **Montúfar-Romero *et al.* (2023)**, seaweed systems, being capable of maximizing carbon capture while maintaining ecological balance, are critical to blue carbon initiatives. The ability of the 50g/tie system to maintain physiological stability and metabolic efficiency enhances its function as a carbon sink, contributing to both marine ecosystem health and global carbon mitigation efforts. Adopting 50g/tie planting may also reduce disease risk and labor intensity, improving economic viability and operational sustainability.

In addition, the consistency observed in the 50g/tie treatment supports more predictable production cycles, a critical factor for market supply chains and downstream processing industries such as carrageenan extraction. Enhanced carbon content further improves the material quality, which is desirable in food, cosmetic, and pharmaceutical applications. These multifaceted benefits highlight the necessity of refining cultivation parameters through empirical research and underscore the value of integrated aquaculture systems that prioritize environmental integrity alongside economic viability. Medium-density planting offers an optimal balance of yield, resource efficiency, and resilience—supporting both commercial and climate mitigation goals in marine aquaculture.

CONCLUSION

This study demonstrated that planting density significantly affects biomass yield, specific growth rate (SGR), and carbon content in *K. alvarezii* cultivated under site-specific conditions in South Sulawesi, Indonesia. The 50g/tie medium density emerged as the most effective across these indicators. Although 75g/tie produced the highest biomass, it was underperformed in physiological efficiency and carbon stability, while 25g/tie showed early carbon advantages though failed to maximize overall yield. The 50g/tie density demonstrated an effective trade-off between productivity and sustainability, offering steady carbon retention and robust growth. These insights can guide farm-level decisions for density calibration aligned with climate-smart aquaculture frameworks. While the study provides empirically grounded density recommendations, future research should explore seasonal cycles, carrageenan quality, nutrient uptake, and potential integration into multi-trophic systems to validate long-term applicability. Ultimately, optimizing planting density is key to harmonizing productivity with ecosystem integrity in seaweed aquaculture.

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