# ANALYSIS OF WATER QUALITY ON THE PRODUCTIVITY OF SEAWEED CULTIVATION OF *Kappaphycus alvarezii* IN WEST SEBATIK DISTRICT, NUNUKAN REGENCY

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## ABSTRACT

Water quality is a critical factor influencing the growth and productivity of seaweed cultivation. This study aimed to analyze the relationship between water quality characteristics and the productivity of *Kappaphycus alvarezii* cultivated using the long-line method in West Sebatik District, Nunukan Regency. The study was conducted from September to December 2025 in three villages, namely Setabu, Binalawan, and Liang Bunyu, using a quantitative approach with an observational and descriptive-analytical design. Water quality parameters measured included temperature, salinity, pH, dissolved oxygen, transparency, current velocity, depth, nitrate, and phosphate. Productivity was evaluated based on growth performance and annual production. The results indicated that all water quality parameters were generally within suitable ranges for seaweed cultivation. Binalawan exhibited the highest transparency (1.50 ± 0.15 m) and phosphate concentration (0.30 ± 0.06 mg $L^{-1}$), resulting in the highest biomass (388 g) and specific growth rate (4.182% $day^{-1}$). Liang Bunyu recorded the highest annual dry production (6,435 tons $year^{-1}$) due to its larger cultivation area. The findings highlight the importance of water quality management and site selection in improving the productivity and sustainability of *K. alvarezii* cultivation.



## INTRODUCTION

Seaweed is one of the most important aquaculture commodities with high economic value and diverse industrial applications. In addition to being utilized as raw material for food products, seaweed derivatives are widely used in pharmaceutical, cosmetic, biotechnology, and agricultural industries. Among commercially cultivated species, *Kappaphycus alvarezii* (formerly known as *Eucheuma cottonii*) has become one of the most economically valuable carrageenan-producing seaweeds because of its rapid growth rate, relatively simple cultivation techniques, and high global demand (Istini & Suhaimi, 2018). According to Hayashi et al. (2022), the increasing demand for carrageenan-based products has stimulated the expansion of *Kappaphycus* farming in many tropical countries, particularly within Southeast Asia. Indonesia, the Philippines, and Tanzania have emerged as major producers contributing significantly to the global seaweed market.

Beyond its economic importance, seaweed cultivation has been recognized as an essential component of sustainable coastal development. Seaweed farming provides employment opportunities, improves household income, strengthens food security, and contributes to poverty alleviation among coastal communities. Previous studies have highlighted the role of seaweed aquaculture as an alternative livelihood strategy, particularly in areas where capture fisheries are vulnerable to seasonal fluctuations and declining fish stocks (Nurwidodo et al., 2018; Oedjoe et al., 2019). Similarly, Sujarwo and Fitriyanny (2016) emphasized that seaweed farming has become an important source of income diversification for small-scale fishers. More recently, Fatmala et al. (2023) reported that the development of seaweed-based economies contributes not only to economic resilience but also to social empowerment and regional development. Furthermore, FAO (2024) recognizes seaweed aquaculture as one of the strategic sectors supporting the concept of blue transformation and sustainable fisheries development.

Indonesia possesses favorable environmental conditions for seaweed cultivation due to its extensive coastline and tropical waters. The country has consistently been among the largest seaweed producers worldwide and continues to expand its production capacity. According to Hurtado et al. (2020), Indonesia dominates global carrageenan seaweed production because of suitable climatic conditions and widespread adoption of long-line farming systems. In recent years, seaweed cultivation has received increasing attention from the government as a strategic commodity capable of enhancing export earnings and improving coastal livelihoods. Consequently, several regions in eastern Indonesia have experienced rapid development of seaweed farming activities.

One of the regions with considerable potential is North Kalimantan Province. The province possesses extensive coastal areas suitable for aquaculture development and exhibits environmental characteristics favorable for seaweed growth. Luthfiyana et al. (2022) reported that the province has experienced remarkable increases in production performance during the last decade. In addition, Zainuddin (2023) documented that the number of seaweed farmers increased by approximately 200.80%, while seaweed production reached 441,152 tons in 2020. Such achievements demonstrate the strategic importance of North Kalimantan as an emerging center of seaweed production. Nevertheless, maintaining high productivity requires a comprehensive understanding of environmental factors affecting cultivation performance.

Sebatik Island, particularly West Sebatik District in Nunukan Regency, represents one of the most important seaweed production areas in North Kalimantan. The local economy is highly dependent on seaweed farming, and most farmers employ the long-line method because of its practicality and relatively low operational costs. Radiarta et al. (2016) reported that thousands of farmers on Sebatik Island manage approximately 100–500 long-line units per household, with a production potential reaching up to 3,000 tons of dried seaweed per month. Despite these promising figures, the area also faces several environmental constraints, including water turbidity, limited protection from wave exposure, and interference from shipping lanes. Such conditions may affect the suitability of cultivation sites and ultimately influence production performance.

Although cultivation techniques are generally similar among farmers, significant differences in productivity are frequently observed among locations. These variations are largely associated with differences in water quality characteristics. Environmental parameters are known to exert considerable influence on the physiological processes, growth rates, and biomass accumulation of *K. alvarezii*. According to Largo et al. (2021), temperature, salinity, water movement, dissolved oxygen, and nutrient concentrations are among the most critical factors controlling the growth of tropical carrageenan-producing seaweeds. Campbell et al. (2019) further emphasized that understanding environmental conditions is fundamental to achieving sustainable seaweed aquaculture and minimizing production risks.

Dissolved oxygen plays a crucial role in supporting photosynthetic and respiratory activities necessary for metabolic processes and biomass formation (Nur et al., 2018). Likewise, light penetration, which is strongly influenced by water transparency, determines photosynthetic efficiency and subsequently affects growth performance. As noted by Muliyadi (2024), adequate light availability enhances biomass production and improves carrageenan quality. Similar findings were previously reported by Mustafa et al. (2017), who observed that reduced transparency limits photosynthetic activity and lowers seaweed productivity. Water current is another important factor because moderate flow facilitates nutrient transport, improves gas exchange, and prevents excessive accumulation of epiphytes on thalli. Pratiwy et al. (2023) indicated that optimal current velocity promotes better growth and increases productivity in tropical seaweed farms.

Nutrient availability, particularly nitrate and phosphate concentrations, also contributes significantly to seaweed growth. These nutrients are essential for cellular metabolism and tissue development. However, excessive nutrient concentrations may induce ecological imbalances and adversely affect water quality (Rahmayanti et al., 2018). Therefore, maintaining an appropriate balance of nutrient concentrations is necessary to ensure optimal production and environmental sustainability. According to Cotas et al. (2023), comprehensive assessments of water quality parameters are indispensable for improving cultivation efficiency and supporting sustainable management practices.

Despite the economic importance of seaweed cultivation in West Sebatik District, studies examining the relationship between environmental conditions and productivity remain limited. Existing studies have mainly focused on site suitability assessments or socioeconomic aspects, while information regarding the influence of water quality variables on cultivation performance at the local scale remains scarce. Considering that microhabitat heterogeneity may lead to differences in environmental characteristics even within the same district, understanding these variations becomes essential for optimizing production and supporting evidence-based management strategies.

Therefore, this study aims to analyze the influence of water quality parameters, including temperature, salinity, pH, dissolved oxygen, transparency, current velocity, depth, nitrate, and phosphate, on the productivity of *Kappaphycus alvarezii* cultivated using the long-line method in three villages of West Sebatik District, namely Setabu, Binalawan, and Liang Bunyu. By employing a descriptive-analytical approach, this study is expected to provide scientific information regarding environmental factors affecting seaweed productivity and contribute to the development of sustainable seaweed aquaculture management in coastal areas.

## METHOD

This study employed a quantitative approach with an observational and descriptive-analytical design to assess water quality conditions and examine their relationship with the productivity of *Kappaphycus alvarezii* cultivation in West Sebatik District, Nunukan Regency. The research was conducted from September to December 2025 in three villages, namely Setabu, Binalawan, and Liang Bunyu, which were selected to represent different environmental characteristics within the district. Seaweed samples were collected directly from farmers practicing the long-line cultivation method, which is widely applied for commercial cultivation because of its simplicity and effectiveness (Hurtado et al., 2020). According to Largo et al. (2021), environmental parameters such as temperature, salinity, pH, dissolved oxygen, nutrient availability, and water movement are among the main factors influencing the growth and carrageenan yield of *K. alvarezii*. Therefore, the independent variables considered in this study included temperature, salinity, pH, dissolved oxygen, transparency, current velocity, depth, nitrate, and phosphate, while productivity was measured as biomass yield per cultivation line and yield per meter of line. The selection of these parameters followed recommendations for evaluating coastal suitability and sustainable seaweed farming systems (Campbell et al., 2019; Cotas et al., 2023), as well as recent findings on Indonesian seaweed cultivation environments (Kambey et al., 2024).

Data collection involved both field measurements and laboratory analyses. In situ observations were conducted using standard oceanographic instruments, including a thermometer for temperature, a refractometer for salinity, a pH meter, a dissolved oxygen meter, and a Secchi disk for transparency. Nutrient concentrations, particularly nitrate and phosphate, were subsequently analyzed by spectrophotometric methods. As reported by Hayashi et al. (2022), water quality assessment is essential for maintaining stable production and ensuring the sustainability of tropical red seaweed cultivation. Productivity data were obtained by weighing harvested biomass and converting the values into kilograms per meter of cultivation line. Descriptive statistics were used to summarize water quality characteristics and productivity, whereas differences among villages were evaluated using one-way analysis of variance (ANOVA). When normality assumptions were not satisfied, the Kruskal-Walli's test was employed, followed by Tukey's or Dunn's post hoc tests to identify significant differences among groups. Similar statistical procedures have been applied in environmental and aquaculture studies to compare spatial variations in water quality and biological production (Pereira et al., 2020; Marinho et al., 2021). Furthermore, multiple linear regression analysis was used to determine the influence of water quality parameters on seaweed productivity at a significance level of 5%, considering that multivariate approaches provide an effective framework for explaining interactions between environmental variables and aquaculture performance (Ward et al., 2020; FAO, 2024).

## RESULT AND DISCUSSION

### Water Quality Characteristics at the Three Cultivation Sites

The results of water quality measurements indicated that all environmental parameters were within ranges generally suitable for seaweed cultivation. Nevertheless, several parameters exhibited noticeable variations among villages, particularly water transparency, current velocity, and nutrient concentrations (nitrate and phosphate). In general, Binalawan Village was characterized by higher transparency and phosphate concentrations, Setabu showed relatively higher nitrate concentrations and dissolved oxygen levels, whereas Liang Bunyu exhibited the highest current velocity but comparatively lower transparency and phosphate concentrations.

**Table 1.**
**Mean ± SD values of physical water quality parameters by village (n = 3 observation points per village)**

| Village | Temperature (°C) | Salinity (‰) | Water Transparency (m) | Current Velocity ($m\ s^{-1}$) | Depth (m) |
|---|---|---|---|---|---|
| Binalawan | 30.70 ± 0.26 | 29.30 ± 0.70 | 1.50 ± 0.15 | 0.81 ± 0.03 | 5.43 ± 4.21 |
| Liang Bunyu | 30.70 ± 0.26 | 29.73 ± 0.25 | 1.32 ± 0.20 | 0.85 ± 0.03 | 5.20 ± 3.73 |
| Setabu | 30.00 ± 0.00 | 29.87 ± 0.23 | 1.43 ± 0.11 | 0.70 ± 0.05 | 4.93 ± 3.57 |

*Source: Research data*

**Table 2.**
**Mean ± SD values of chemical water quality parameters by village (n = 3 observation points per village)**

| Village | Dissolved Oxygen ($mg\ L^{-1}$) | pH | Nitrate ($mg\ L^{-1}$) | Phosphate ($mg\ L^{-1}$) |
|---|---|---|---|---|
| Binalawan | 5.27 ± 0.75 | 7.80 ± 0.00 | 0.28 ± 0.03 | 0.30 ± 0.06 |
| Liang Bunyu | 5.87 ± 0.74 | 8.10 ± 0.00 | 0.26 ± 0.03 | 0.10 ± 0.02 |
| Setabu | 6.43 ± 0.12 | 7.80 ± 0.00 | 0.40 ± 0.02 | 0.20 ± 0.04 |

*Source: Research data*

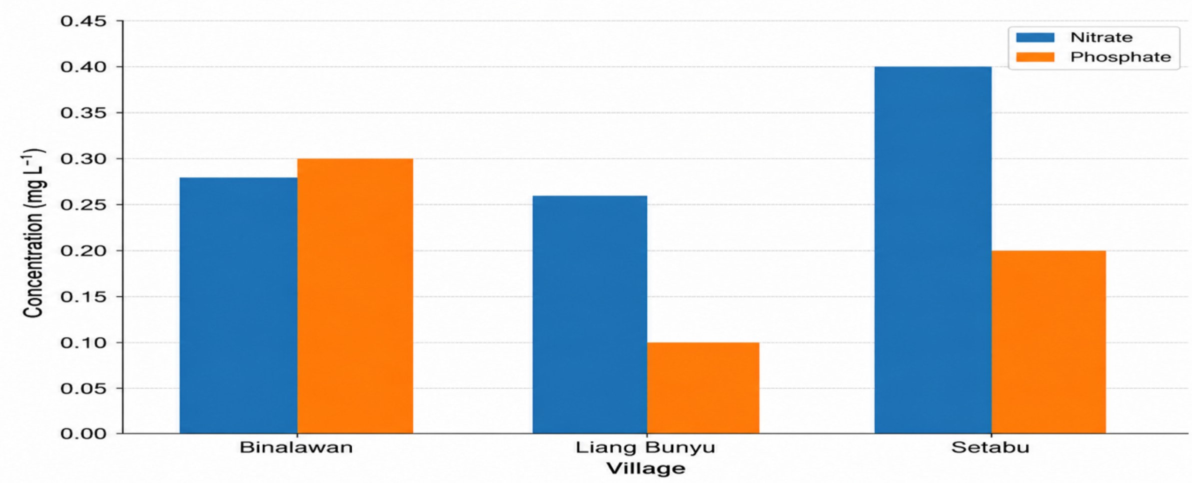
Tables 1 and 2 demonstrate that Binalawan Village generally had greater water transparency than Setabu and Liang Bunyu. Adequate transparency enhances light penetration into the water column, thereby increasing photosynthetic efficiency and promoting biomass accumulation. According to Largo et al. (2021), sufficient light availability is essential for carrageenan-producing seaweeds because it supports photosynthesis and facilitates the synthesis of structural polysaccharides. Consequently, waters with higher transparency may provide favorable conditions for seaweed growth and production, provided that other environmental variables such as temperature, salinity, pH, and dissolved oxygen remain within acceptable ranges.

With respect to nutrients, nitrate concentrations were highest in Setabu, whereas phosphate concentrations were highest in Binalawan. Liang Bunyu exhibited the lowest phosphate concentration among the three locations. These findings are ecologically important because nitrogen and phosphorus perform different physiological functions in seaweed metabolism. Nitrogen is primarily involved in protein synthesis and cellular division, whereas phosphorus is closely associated with ATP production, membrane formation, and carbohydrate metabolism. Therefore, elevated nitrate concentrations do not necessarily result in maximum growth if phosphorus availability or light penetration becomes the limiting factor. This pattern may explain why Setabu, despite possessing relatively high nitrate concentrations, did not consistently produce superior growth performance compared with Binalawan, where phosphate concentration and water transparency were relatively higher.

**Figure 1.**

Comparison of average nitrate and phosphate concentrations among the three villages.

Source: Research data




*Source: Research data*

Figure 1 illustrates that the highest nitrate concentration was recorded in Setabu, whereas the highest phosphate concentration occurred in Binalawan and the lowest phosphate concentration was observed in Liang Bunyu. The nutrient distribution pattern is noteworthy because the site characterized by relatively high phosphate availability exhibited better growth and productivity performance. Previous studies have emphasized that balanced nutrient availability is essential for sustaining metabolic activities and maximizing seaweed production (Cotas et al., 2023; Hayashi et al., 2022).

**Growth Performance of *Kappaphycus alvarezii***

Seaweed growth was monitored from an initial seed weight of 50 g until the seventh week of cultivation. Among the three study sites, Binalawan exhibited the highest final biomass and specific growth rate, followed by Setabu, whereas Liang Bunyu recorded the lowest values.

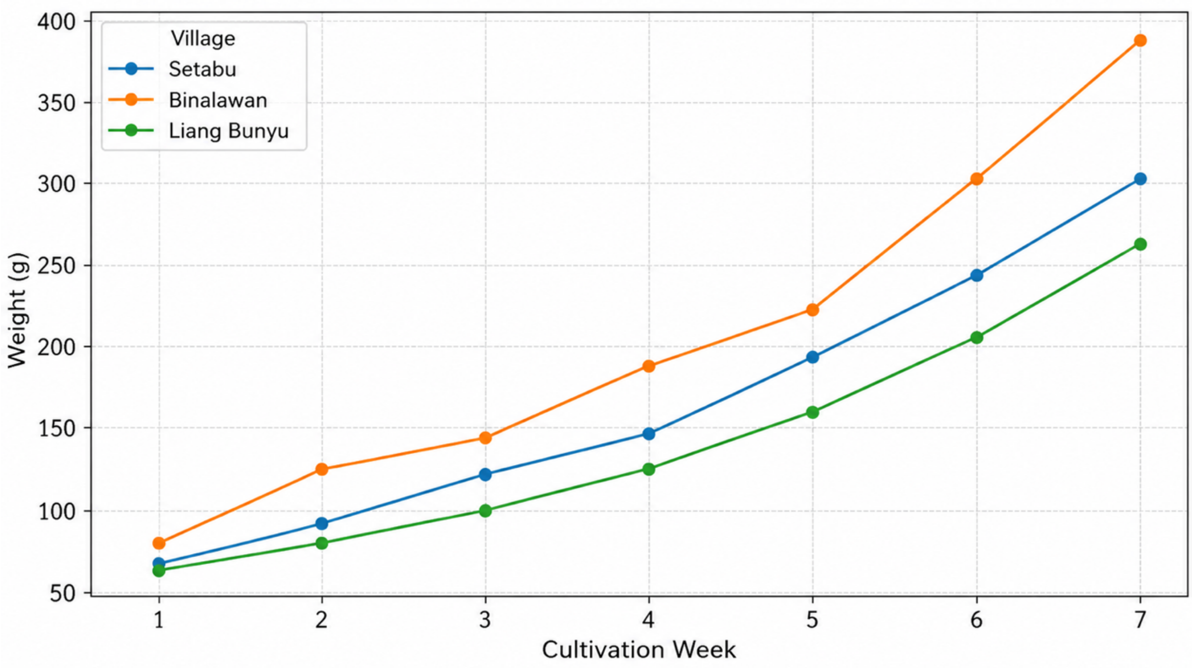
**Table 3.**
Summary of seaweed growth performance up to the seventh week

| Village | Initial Weight (g) | Weight at Week 7 (g) | Total Weight Gain (g) | Average Weight Gain (g week$^{-1}$) | Specific Growth Rate (% day$^{-1}$) |
|---|---|---|---|---|---|
| Setabu | 50 | 304 | 254 | 36.29 | 3.684 |
| Binalawan | 50 | 388 | 338 | 48.29 | 4.182 |
| Liang Bunyu | 50 | 267 | 217 | 31.00 | 3.419 |

*Source: Research data*

The results revealed that Binalawan produced the highest biomass at week seven (388 g) and the highest specific growth rate (4.182% day$^{-1}$). Setabu showed intermediate performance, with a final biomass of 304 g and a specific growth rate of 3.684% day$^{-1}$. In contrast, Liang Bunyu exhibited the lowest growth performance, producing a final biomass of 267 g and a specific growth rate of 3.419% day$^{-1}$.

**Figure 2.**
Weekly growth curve of seaweed cultivated in the three villages




*Source: Research data*

Figure 2 demonstrates that biomass increased continuously throughout the cultivation period in all villages. However, Binalawan consistently maintained the highest biomass values, and the increase became more pronounced between the fourth and seventh weeks. Setabu displayed a relatively stable intermediate growth pattern, whereas Liang Bunyu showed the slowest increase in biomass.

The superior growth performance observed in Binalawan may be attributed to more favorable environmental conditions, particularly higher water transparency and phosphate concentrations. Adequate light penetration enhances photosynthetic efficiency and facilitates carbohydrate accumulation, while phosphorus availability supports cellular metabolism and energy transfer processes. Similar findings have been reported by Hayashi et al. (2022), who demonstrated that environmental conditions strongly influence the growth performance of tropical carrageenan-producing seaweeds. Furthermore, Largo et al. (2021) emphasized that interactions among light intensity, nutrient availability, and hydrodynamic conditions determine biomass accumulation and overall productivity.

**Seaweed Productivity at the Three Study Sites**

Seaweed productivity was analyzed at two different scales, namely productivity per cultivation unit (fresh and dry weight per cultivation line) and annual total production, which is influenced by cultivated area and the number of farmers. Consequently, locations with superior productivity per unit do not necessarily generate the highest total production.

**Table 4.**

Summary of seaweed productivity among the three villages

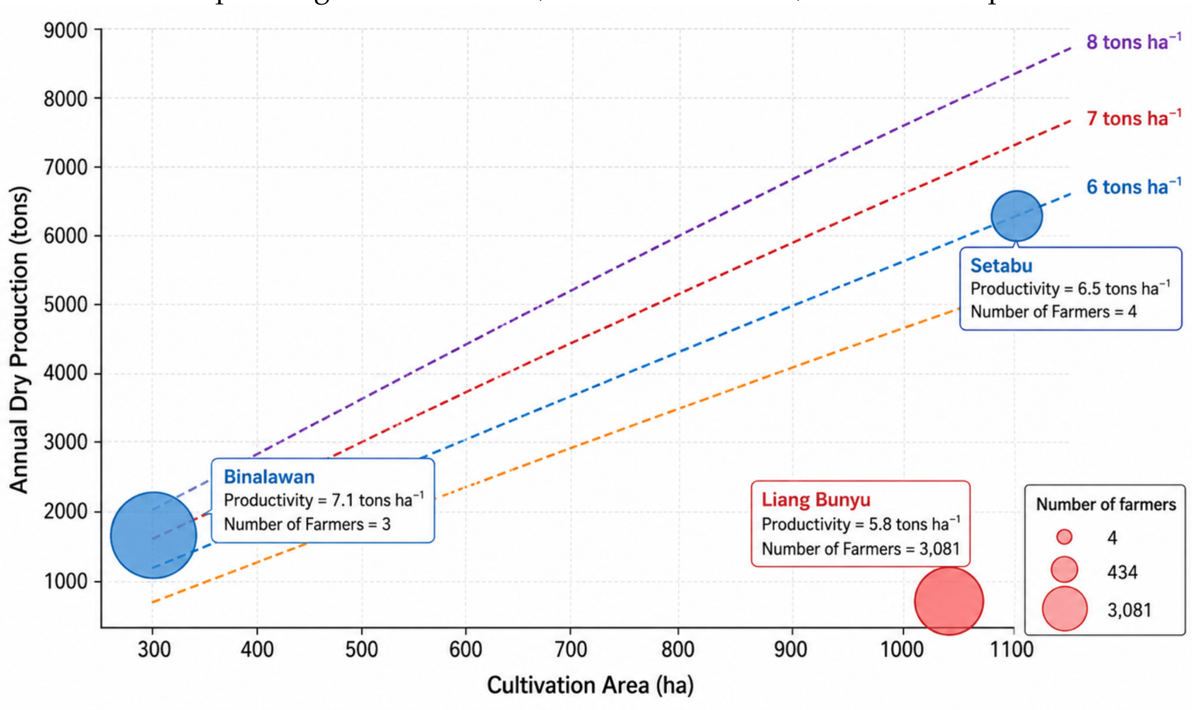
| Village | Fresh Weight per Line (g) | Dry Weight per Line (g) | Cultivation Area (ha) | Number of Farmers | Annual Fresh Production (tons) | Annual Dry Production (tons) |
|---|---|---|---|---|---|---|
| Setabu | 304 | 39.5 | 300 | 4 | 15,000 | 1,950 |
| Binalawan | 388 | 50.4 | 320 | 3 | 16,500 | 2,288 |
| Liang Bunyu | 267 | 34.7 | 1,100 | 3,081 | 49,500 | 6,435 |

*Source: Research data*

The summary presented in Table 5 indicates that Binalawan exhibited the highest productivity per cultivation line, both in terms of fresh and dry biomass. This result highlights the superior production efficiency of this location. However, Liang Bunyu achieved the highest estimated annual production because of its substantially larger cultivation area and greater number of production units. Therefore, regional production capacity does not always correspond directly to productivity per unit.

**Figure 3.**

Relationship among cultivation area, number of farmers, and seaweed production




*Source: Research data*

Figure 3 illustrates the relationship between cultivation area (ha) and annual dry seaweed production (tons year$^{-1}$), with bubble size representing the number of farmers. Liang Bunyu occupied the most extreme position along both axes, with a cultivation area of approximately 1,100 ha and an annual dry seaweed production of 6,435 tons. This finding suggests that the large-scale production observed in Liang Bunyu was primarily determined by the extensive cultivation area rather than by higher productivity per cultivation unit.

At a smaller scale, Setabu possessed a cultivation area of approximately 300 ha and produced 1,950 tons of dry seaweed annually, whereas Binalawan, with a slightly larger area of 320 ha, generated 2,288 tons year$^{-1}$. Interestingly, despite the similarity in cultivation area between Setabu and Binalawan, annual production in Binalawan was higher. This observation suggests that environmental conditions and production efficiency contributed significantly to productivity differences between these villages.

Overall, the comparative analysis demonstrates that the dominance of annual production in Liang Bunyu is mainly attributable to the larger cultivation area, whereas Binalawan exhibited superior production efficiency at the unit level. These findings emphasize that total production and productivity are influenced by different factors. While production volume is closely associated with cultivation scale, productivity per unit is more strongly affected by environmental conditions and water quality characteristics. Therefore, improving water quality management may represent an effective strategy for increasing seaweed productivity without necessarily expanding cultivation areas.

The findings of this study demonstrate that differences in seaweed productivity among villages were associated with variations in water quality characteristics. Although all locations generally met the environmental requirements for seaweed cultivation, the magnitude of productivity differed substantially. Binalawan consistently exhibited superior growth and productivity performance, suggesting that a combination of favorable environmental factors created more suitable conditions for *K. alvarezii* cultivation.

The higher productivity observed in Binalawan appears to result from the synergistic effects of greater water transparency and phosphate availability. Adequate light penetration increases photosynthetic efficiency, while phosphorus supports energy transfer and cellular metabolism. According to Hayashi et al. (2022), productivity in tropical seaweed farming is often determined by the interaction of multiple environmental variables rather than by a single factor. This observation is consistent with the present study, where productivity was highest in the location exhibiting the most balanced environmental conditions.

In contrast, Setabu demonstrated intermediate productivity despite possessing the highest nitrate concentration. This finding indicates that nutrient availability alone does not guarantee optimal production. As suggested by Campbell et al. (2019), productivity is often constrained by the most limiting environmental factor. In the case of Setabu, lower transparency compared with Binalawan may have reduced photosynthetic efficiency, thereby limiting the potential benefits of elevated nitrate concentrations.

Liang Bunyu presents an interesting case because it recorded the highest annual production despite having the lowest productivity per cultivation unit. This discrepancy highlights the distinction between production scale and production efficiency. The large cultivation area in Liang Bunyu enabled greater total output even though environmental conditions were less favorable for maximizing growth. Similar patterns have been reported in commercial aquaculture systems, where total production is strongly influenced by operational scale, whereas productivity reflects the efficiency of environmental resource utilization (FAO, 2024).

The present findings also support the concept that water quality management is a critical component of sustainable seaweed farming. Improving transparency through site selection, maintaining balanced nutrient availability, and ensuring appropriate hydrodynamic conditions may significantly enhance productivity without requiring expansion of cultivation areas. Such an approach is particularly relevant for coastal regions where space availability is limited and environmental sustainability has become an increasingly important consideration.

Overall, the study confirms that environmental heterogeneity within a relatively small geographical area can generate substantial differences in seaweed cultivation performance. Understanding these relationships is essential for optimizing site selection, improving management practices, and increasing the economic efficiency of seaweed farming in West Sebatik District and other coastal regions with similar environmental characteristics.

## CONCLUSION

The results of this study indicate that variations in water quality characteristics among villages contributed to differences in the growth and productivity of Kappaphycus alvarezii cultivated in West Sebatik District, Nunukan Regency. Although all study sites generally exhibited environmental conditions suitable for seaweed cultivation, Binalawan consistently showed the highest growth performance and productivity per cultivation unit. This superior performance was associated with higher water transparency and phosphate concentrations, which enhanced photosynthetic efficiency and supported cellular metabolism. Setabu displayed intermediate productivity despite having the highest nitrate concentration, suggesting that nutrient availability alone does not guarantee maximum production. Meanwhile, Liang Bunyu recorded the highest annual production owing to its substantially larger cultivation area, despite exhibiting lower productivity per unit.

These findings demonstrate that productivity and total production are influenced by different factors. While total production is largely determined by cultivation scale, productivity per unit is more strongly affected by environmental quality. Therefore, appropriate site selection and effective management of water quality parameters, particularly transparency, nutrient availability, and hydrodynamic conditions, are essential for improving the efficiency and sustainability of seaweed farming. The study highlights the importance of considering environmental heterogeneity in optimizing K. alvarezii cultivation and provides useful information for developing sustainable seaweed aquaculture in West Sebatik District and similar coastal regions.

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