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Land Suitability for *Kappaphycus alvarezii* Aquaculture in Loleo Waters, Central Halmahera

(Kesesuaian Lahan Budidaya Kappaphycus alvarezii Di Perairan Loleo, Halmahera Tengah)

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Abstract. This study aimed to assess the land suitability for the cultivation of Kappaphycus alvarezii in the coastal waters of Loleo Village, South Weda District, Central Halmahera Regency, Indonesia. Data were collected from January to February 2026 across seven observation stations. The analyzed parameters included depth, water transparency, temperature, pH, salinity, dissolved oxygen (DO), nitrate, and phosphate. Land suitability analysis was conducted using a weighted scoring method based on the relative influence of each parameter. The results were classified into three suitability classes: highly suitable (S1), moderately suitable (S2), and unsuitable (N). The results indicated that the overall water conditions were generally within the optimal range for the growth of K. alvarezii, particularly in terms of salinity, pH, and dissolved oxygen. However, relatively high temperatures and low nutrient concentrations were identified as the main limiting factors. The spatial analysis showed that the study area consisted of 37 ha classified as highly suitable (S1), 113 ha as moderately suitable (S2), and 63 ha as unsuitable (N), with a total potential cultivation area of 150 ha. These findings suggest that the Loleo waters have significant potential for seaweed aquaculture development, provided that adaptive management strategies are implemented.
Keywords: Central Halmahera; Kappaphycus alvarezii; land suitability; water quality

INTRODUCTION

Global trade in seaweed products has shown a significant upward trend in recent years. In 2022, the global export value of seaweed increased by 26% compared to the previous year, reaching USD 1.6 billion. This increase was primarily driven by a surge in exports from Indonesia to the global market. As a result, Indonesia ranked as the world's largest seaweed exporter by value, followed by the Republic of Korea and Chile. Collectively, these three countries accounted for approximately 58% of the total global seaweed export value in 2022, highlighting Indonesia's strategic role in the global seaweed supply chain (FAO, 2024).

One of the most widely farmed seaweed species is *Kappaphycus alvarezii*, a tropical macroalga with high economic value and a major source of κ-carrageenan for the food, pharmaceutical, cosmetic, and various industrial applications (Rudke et al., 2020; Kumar et al., 2022). This species exhibits relatively fast growth rates and strong adaptability to tropical environmental conditions, making it a key commodity in seaweed aquaculture (Hinaloc and Roleda, 2021). In addition, *K. alvarezii* farming provides significant socio-economic benefits to coastal communities, as it requires relatively low capital investment, utilizes simple technology, and has a short production cycle (Rimmer et al., 2021).

As an archipelagic country, Indonesia has substantial potential for the development of *K. alvarezii* aquaculture across its coastal regions. Central Halmahera Regency is one of the areas with such potential, with marine waters covering approximately 73% of its total administrative area. Seaweed farming activities in this region have been developing, particularly in the coastal waters of Loleo, South Weda District. This indicates that the area has strong potential to be further developed into a productive and sustainable seaweed farming zone.

The success of seaweed aquaculture is strongly influenced by the suitability of environmental conditions. Water quality parameters such as temperature, salinity, pH, dissolved oxygen, water transparency, and nutrient availability play crucial roles in determining seaweed growth and productivity (Makwana, 2011; Ullah et al., 2023). Furthermore, declining water quality due to anthropogenic activities can negatively affect aquaculture performance (Zahroh et al., 2019). Therefore, site selection is a key factor in ensuring successful aquaculture production, as widely recognized that aquaculture performance is highly dependent on site suitability (Sanchez-Jerez et al., 2015).

Land suitability analysis for seaweed aquaculture has been conducted in various regions, including South Sulawesi, North Kalimantan, Lampung, and East Nusa Tenggara (Yulianto et al., 2017; Maradhy et al., 2022; Sarjito et al., 2022; Kamlasi et al., 2025). However, despite the ongoing seaweed farming activities in Loleo waters, Central Halmahera, scientific information regarding land suitability in this area remains limited. This knowledge gap highlights the need for a comprehensive assessment to support more optimal and sustainable aquaculture management. Therefore, this study aims to evaluate the land suitability for *K. alvarezii* aquaculture in Loleo waters, Central Halmahera, based on water quality parameters. The findings of this study are expected to provide a scientific basis for planning and developing sustainable seaweed aquaculture in Central Halmahera Regency.

METHOD

The sentences under the sub chapters are written without any spacing with the title. If there is a mathematical equation, the equation is made with the equation editor and numbered according to the order of the existing equations. Gel Strength Testing (sub of sub chapters is written underscore in capital letters at the beginning of a word) Sentences under sub chapters are written without spacing with the title.

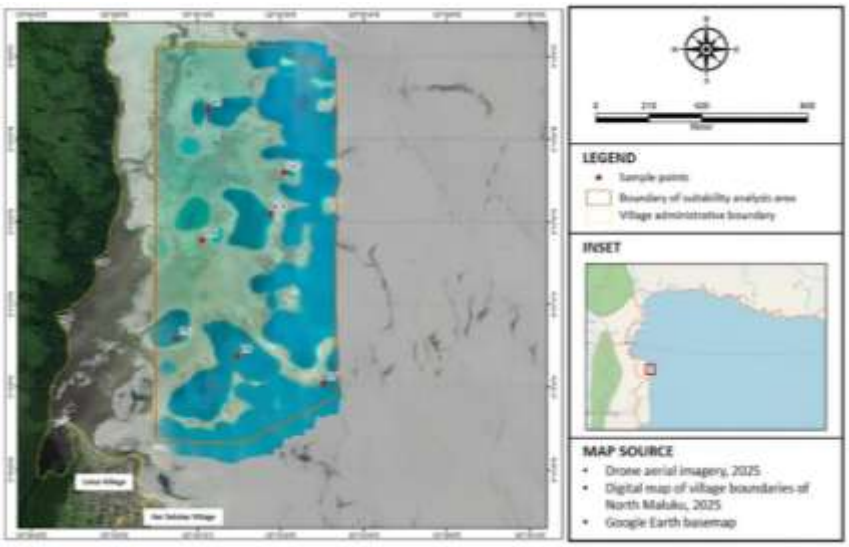
Study Area

This study was conducted in the coastal waters of Loleo, South Weda District, Central Halmahera Regency, North Maluku, Indonesia. The area is recognized as one of the active cultivation sites for *Kappaphycus alvarezii*, managed by local seaweed farming communities. The waters of Loleo are characterized by relatively sheltered coastal conditions, making them suitable for seaweed cultivation activities. Environmental variability in this area is influenced by factors such as water depth, light penetration, and proximity to farming structures. Data were collected from seven observation stations (L1–L7), which were selected using a purposive sampling approach. The selection of stations was based on the representation of environmental gradients and variations in cultivation intensity, including differences in depth, water clarity, and proximity to farming areas. The spatial distribution of the sampling stations is presented in Figure 1.

Data Collection

Data collection was carried out through a combination of in situ measurements and ex situ laboratory analyses. In situ parameters included water temperature, salinity, pH, dissolved oxygen (DO), water transparency, and depth. Water temperature was measured using a digital thermometer, salinity using a refractometer, pH using a calibrated pH meter, and dissolved oxygen using a DO meter. Water transparency was determined using a Secchi disk, while water depth was measured at each station. All in situ measurements were conducted directly at each sampling station during the field survey period. To ensure data reliability, measurements were performed under similar environmental conditions. For ex situ analysis, water samples (300 mL) were collected from each station using clean sample bottles. The samples were stored in a

cool box to maintain their integrity during transportation and subsequently analyzed in the laboratory to determine nitrate and phosphate concentrations. Laboratory analyses were conducted at PT. Water Laboratory Nusantara (WLN), Manado, North Sulawesi (N 1°29′27.43″; E 127°51′43.50″).



Gambar 1. Research Location in Loleo Waters.

Data Analysis

Land suitability for *Kappaphycus alvarezii* cultivation was evaluated using a weighted scoring approach based on selected water quality parameters. Each parameter was classified into three suitability classes: highly suitable (S1), moderately suitable (S2), and unsuitable (N), which were assigned scores of 5, 3, and 1, respectively. A weighting system was applied to account for the relative importance of each parameter. Temperature, pH, salinity, and dissolved oxygen (DO) were considered dominant variables and assigned a weight of 15 each, while depth, water transparency, nitrate, and phosphate were categorized as non-dominant variables and assigned a weight of 10 each. The total weight of all parameters was 100. The criteria and threshold values used to classify each parameter into the respective suitability classes are presented in Table 1.

The overall suitability score for each observation station was calculated by summing the weighted scores of all parameters. The maximum possible score (ΣS_{max}) was obtained by multiplying the highest score (5) by the total weight (100), resulting in a value of 500. Conversely, the minimum possible score (ΣS_{min}) was calculated by multiplying the lowest score (1) by the total weight, resulting in a value of 100. The class interval (x) was determined using the following equation:

$$x = \frac{\sum S_{max} - \sum S_{min}}{n}$$

where *n* represents the number of suitability classes (n = 3). Based on this calculation, the class interval was 133. Based on the calculated interval, the suitability classes were defined as follows: highly suitable (S1) for scores greater than 367, moderately suitable (S2) for scores ranging from 234 to 367, and unsuitable (N) for scores less than 234. Furthermore, spatial analysis was conducted by generating thematic layers for each parameter and reclassifying them according to the defined suitability thresholds. All layers were then integrated using a weighted overlay approach within a Geographic Information System (GIS) environment to produce the final land suitability map.

Table 1. Land suitability criteria for *Kappaphycus alvarezii* cultivation in Loleo Waters, Central Halmahera Regency

Parameter	Range	Score (A)	Weight (B)	AxB	References
Depth (m)	0.1-5	5	10	50	Wenno et al., 2016; Pong-Masak & Sarira, 2020; Momo et al., 2024
	5-10	3		30	
	<0.1 or >10	1		10	
Transparency (m)	<3	5	10	50	Jamaluddin *et al*., 2019
	3-5	3		30	
	>5	1		10	
Temperature (°C)	24-30	5	15	75	Jamaluddin *et al*., 2019
	20-24	3		45	
	< 20 or > 30	1		15	
pH	6.5-8.5	5	15	75	Jamaluddin *et al*., 2019
	4-6.5 or 8.5-9.5	3		45	
	< 4 or > 9.5	1		15	
Salinity (ppt)	32-34	5	15	75	Ihsan *et al*., 2021
	28-32	3		45	
	<28 or >35	1		15	
DO (mg/L)	>6	5	15	75	Jamaluddin *et al*., 2019
	4-6	3		45	
	<4	1		15	
Nitrate (mg/L)	0.9-3.2	5	10	50	Jamaluddin *et al*., 2019
	0.1-0.8 or 3.3-3.4	3		30	
	< 0.1 or > 3.4	1		10	
Phosphate (mg/L)	0.2-0.5	5	10	50	Jamaluddin *et al*., 2019
	0.1-0.2 or 0.5-1.0	3		30	
	< 0.1 or > 1.0	1		10	

RESULTS AND DISCUSSION

Water Quality Characteristics

The measured water quality parameters across the seven observation stations (L1–L7) are presented in Table 2. Overall, the results indicate spatial variability in environmental conditions, which plays a critical role in determining the suitability of the area for seaweed aquaculture. Water depth ranged from 1.00 to 19.00 m, with the highest value recorded at station L7 and the lowest at L4. This variation reflects heterogeneity in seabed morphology, which can influence light penetration and water column dynamics. In general, *Kappaphycus alvarezii* is optimally cultivated at depths of 0.2–5 m, although it may tolerate depths of up to approximately 10 m under certain conditions (Wenno et al., 2016; Pong-Masak & Sarira, 2020; Momo et al., 2024). Therefore, stations exceeding this range may experience reduced photosynthetic efficiency due to limited light availability, potentially lowering their suitability.

Table 3. Water quality characteristics at the seaweed aquaculture development sites in Loleo, Central Halmahera Regency.

Parameter	L1	L2	L3	L4	L5	L6	L7
Depth (m)	8.50	1.50	9.50	1.00	5.00	15.00	19.00
Transparency (m)	5.60	1.50	6.00	1.00	5.00	6.00	6.00
Temperature (°C)	30.68	31.69	31.97	33.16	32.58	30.00	31.25
pH	7.84	7.81	7.81	7.85	7.69	7.80	7.28
Salinity (ppt)	32.11	32.14	31.78	32.28	31.14	32.06	32.74
DO (mg/L)	8.12	7.78	8.36	8.88	7.92	8.17	7.79
Nitrate (mg/L)	0.04	<0.02	0.02	0.03	0.02	0.02	0.02
Phosphate (mg/L)	0.01	0.01	0.01	0.01	<0.01	<0.01	<0.01

Water transparency ranged from 1.00 to 6.00 m, with higher values observed at stations L3, L6, and L7, and the lowest at L4. Transparency is a key factor influencing light availability for photosynthesis. Optimal transparency for seaweed growth has been reported at 0.3–1.0 m (Ullah et al., 2023), while values between 2–5 m are still considered suitable for *K. alvarezii* (Abdullah et al., 2020). Higher transparency indicates clearer waters; however, when combined with elevated temperatures, it may increase light stress. Conversely, low transparency may limit photosynthetic activity.

Water temperature ranged from 30.00 to 33.16 °C, exceeding the optimal range for seaweed growth. Optimal temperatures are generally reported between 22.8–29.2 °C (Ullah et al., 2023), with recommended cultivation ranges of 20–28 °C and tolerance up to 31 °C for *K. alvarezii* (Abdullah et al., 2020). The relatively high temperatures observed suggest potential thermal stress, which may reduce metabolic efficiency and increase respiration rates. This indicates that temperature is one of the main limiting factors in the study area, particularly at station L4.

The pH values ranged from 7.28 to 7.85, indicating relatively stable conditions from neutral to slightly alkaline. This range falls within the optimal conditions for seaweed growth (7.5–8.5) (Ullah et al., 2023) and is suitable for *K. alvarezii* (Abdullah et al., 2020). Such stability supports physiological processes, particularly nutrient uptake. Salinity ranged from 31.14 to 32.74 ppt, which is within the optimal range for seaweed growth (24–34 ppt) (Ullah et al., 2023) and suitable for *K. alvarezii* (18–35 ppt) (Abdullah et al., 2020). The relatively homogeneous salinity values indicate that this parameter is not a limiting factor but rather supports osmotic balance.

Dissolved oxygen (DO) concentrations ranged from 7.78 to 8.88 mg/L, indicating well-oxygenated waters. DO levels above 5 mg/L are generally considered suitable for seaweed growth (Ullah et al., 2023), while *K. alvarezii* can tolerate 3–8 mg/L (Abdullah et al., 2020). The high DO concentrations suggest favorable environmental conditions for metabolic activity. In contrast, nitrate (<0.02–0.04 mg/L) and phosphate (<0.01–0.01 mg/L) concentrations were relatively low. Optimal growth of *K. alvarezii* has been reported at nitrate concentrations of 0.01–0.07 mg/L and phosphate concentrations of 0.1–0.2 mg/L (Simatupang et al., 2021). These findings indicate that nutrient limitation may occur, particularly under intensive cultivation conditions, making nutrients another potential limiting factor.

Land Suitability Analysis

The spatial distribution of land suitability for *Kappaphycus alvarezii* aquaculture in Loleo waters is shown in Figure 2. The study area was classified into three suitability classes: highly suitable (S1), moderately suitable (S2), and unsuitable (N). The results show that 37 ha were classified as highly suitable (S1), 113 ha as moderately suitable (S2), and 63 ha as unsuitable (N). The total potential area for aquaculture development (S1 and S2) reached 150 ha. The dominance of the moderately suitable class (S2) indicates that most of the study area has environmental conditions that are adequate but not optimal for seaweed aquaculture.

This pattern is consistent with the observed environmental conditions, where most parameters fall within acceptable ranges, but certain limiting factors particularly high temperature and low nutrient concentrations reduce overall suitability. Similar findings have been reported in other regions such as South Sulawesi, North Kalimantan, and Lampung, where environmental parameters play a decisive role in determining aquaculture suitability (Yulianto et al., 2017; Maradhy et al., 2022; Sarjito et al., 2022). From a management perspective, these results highlight the need for adaptive strategies to improve aquaculture performance. Such strategies may include adjusting planting schedules to avoid peak temperature periods and

implementing nutrient management practices to enhance productivity. These measures are essential to ensure the sustainability and efficiency of seaweed aquaculture in Loleo waters.

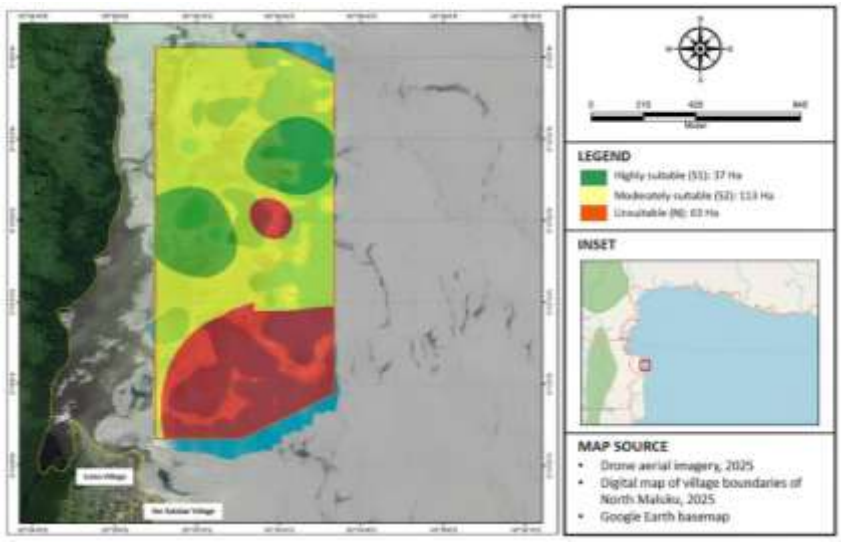


Figure 2. Land suitability map for *Kappaphycus alvarezii* aquaculture in Loleo waters, Central Halmahera Regency

CONCLUSIONS AND SUGGESTIONS

This study demonstrates that the coastal waters of Loleo have considerable potential for *Kappaphycus alvarezii* aquaculture development, with a total suitable area of 150 ha classified as highly suitable (S1) and moderately suitable (S2), predominantly within the S2 category. Overall, the environmental conditions are generally favorable, particularly in terms of salinity, pH, and dissolved oxygen. However, relatively high water temperatures and low nutrient concentrations (nitrate and phosphate) were identified as the main limiting factors affecting site suitability. These findings highlight the importance of site-specific and adaptive management strategies to optimize production and ensure the sustainability of seaweed aquaculture in the study area.

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