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Research Article

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Spatial Modeling of Seaweed (*Kappaphycus alvarezii*) Farming Suitability Using GIS in Tinangkung Waters, Central Sulawesi, Indonesia

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ABSTRACT

Particularly in the waters of Tinangkung, Central Sulawesi, the management of seaweed through marine spatial planning and evidence-based site selection remains extremely limited. The objective of this study was to assess the suitability of the environment for *Kappaphycus alvarezii* farming based on spatial modeling using a Geographic Information System (GIS). Eight environmental parameters were tested, namely depth, temperature, salinity, brightness, current velocity, nutrients (nitrate and phosphate), pH, and dissolved oxygen (DO), which were integrated into GIS software using the weighted overlay method to produce a land suitability map. The results indicated that the area was divided into three suitability classes, namely highly suitable (S1) covering an area of 722.79 ha (31.8%), suitable (S2) covering an area of 1,616.72 ha (66.6%), and unsuitable (N) covering an area of 88.29 ha (3.6%). The central and southern zones of Tinangkung Bay are classified as highly suitable (S1) with stable water characteristics, high clarity, and optimal oxygen and salinity content. In contrast, coastal and estuarine areas are classified as less suitable (S2) due to the influence of land runoff, which alters salinity and pH. GIS-based modeling is effective in integrating environmental data to assist in a comprehensive mapping of marine aquaculture suitability. This study produced the first water suitability map for *K. alvarezii* aquaculture in Tinangkung waters, which can serve as a scientific basis for the formulation of marine spatial planning policies and sustainable seaweed aquaculture management in Central Sulawesi.

Keywords: *Spatial analysis; GIS; Kappaphycus alvarezii; water suitability; coastal zone*

ABSTRAK

Pengelolaan rumput laut dengan merencanakan pengelolaan ruang laut serta pemilihan lokasi berbasis bukti ilmiah masih sangat terbatas terutama di perairan Tinangkung, Sulawesi Tengah. Tujuan penelitian ini adalah untuk menilai Tingkat kesesuaian lingkungan terhadap budidaya *Kappaphycus alvarezii* berbasis pemodelan spasial berbasis Sistem Informasi Geospasial (SIG). Delapan parameter lingkungan di uji yaitu kedalaman, suhu, salinitas, kecerahan, kecepatan arus, nutrien (nitrat dan fosfat), pH, dan oksigen terlarut (DO), diintegrasikan pada perangkat lunak GIS menggunakan metode weighted overlay agar menghasilkan peta kesesuaian lahan. Hasil yang diperoleh menunjukkan bahwa wilayah terbagi ke dalam tiga kelas kesesuaian, yaitu sangat sesuai (S1) seluas 722,79 ha (31,8%), sesuai (S2) seluas 1.616,72 ha (66,6%), dan tidak sesuai (N) seluas 88,29 ha (3,6%). Zona tengah dan selatan teluk Tinangkung tergolong sangat sesuai (S1) dengan karakteristik perairan yang stabil, kecerahan tinggi, serta kandungan oksigen dan salinitas yang optimal. Sebaliknya, wilayah pesisir dan muara tergolong kurang sesuai (S2) yang dipengaruhi oleh limpasan daratan yang mengubah salinitas dan pH. Pemodelan berbasis SIG efektif dalam mengintegrasikan data lingkungan untuk membantu pemetaan kesesuaian budidaya laut secara komprehensif. Penelitian ini menghasilkan peta kesesuaian lahan pertama untuk budidaya *K. alvarezii* di perairan Tinangkung, yang dapat menjadi dasar ilmiah bagi penyusunan kebijakan tata ruang laut dan pengelolaan budidaya rumput laut berkelanjutan di Sulawesi Tengah.

Kata kunci: Analisis spasial; GIS; *Kappaphycus alvarezii*; kesesuaian lahan; zona pesisir

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1. Introduction

Seaweed is one of the rapidly growing macroalgae commodities due to its adaptability and fast and sustainable growth cycle. Similarly, the red seaweed *Kappaphycus alvarezii* is recognized as an important economic resource in tropical regions, primarily due to its role as the main raw material for carrageenan and its potential for carbon sequestration as part of efforts to mitigate climate change. This type of seaweed has a wide range of potential applications in various industries, including the food, pharmaceutical, and cosmetics industries (Cham and Yasman, 2025; García-Poza et al., 2020). Global demand for seaweed has continued to increase in recent years. According to the most recent estimates, global seaweed production was 31.8 million tons in 2018, 34.6 million tons in 2019, and 50 million tons in 2020 (Basyuni et al., 2024; Sugumaran et al., 2022). In Indonesia, seaweed contributes as a major source of income for coastal seaweed communities. This is because the capital and inputs required for seaweed farming are relatively lower than those for other coastal aquaculture activities (Rimmer et al., 2021; Rahmat and Neilson, 2023). Although its potential is enormous, the cultivation process depends on water suitability; various environmental pressures and management factors (changes in the physical and chemical conditions of the water, an increase in disease cases, and competition for the use of marine space) also play a role (Laktuka et al., 2023; Haque and Mahmud, 2025; Rupert et al., 2022).

Parameters such as temperature, salinity, depth, current velocity, light intensity, and nutrient content (nitrate and phosphate) directly affect the growth and quality of thallus. Fluctuations in these factors can cause physiological stress in plants and increase susceptibility to diseases such as ice-ice, which is often the main cause of yield decline in various tropical regions. Ward et al. (2022) reported that ice-ice disease (tissue bleaching and necrosis) is one of the most common diseases affecting seaweed. The factors causing this disease are environmental stress and changes in the epiphytic microbiome or pathogens that take advantage of the weakened condition of the seaweed thallus (Tisera, 2024; Tahiluddin & Terzi, 2021). Singh et al. (2025) reported that nutrient imbalance can also increase epiphyte growth, which impacts the quality and yield of seaweed harvests. To anticipate these challenges, an analytical approach that comprehensively integrates various environmental parameters is required.

In general, in coastal areas of Indonesia, the determination of seaweed cultivation locations is still based on the empirical experience of the community without considering measurable environmental data. This includes Banggai Kepulauan Regency. As a result, several areas that are ecologically unsuitable continue to be utilized, thereby reducing efficiency and increasing the risk of crop failure (Coffey et al., 2025; Fricke et al., 2025). Limited spatial data and the absence of comprehensive water suitability maps also hinder evidence-based marine spatial planning in this region.

A spatial approach based on Geographic Information System (GIS) technology and remote sensing has proven effective in integrating multi-environmental parameters into a location suitability matrix for maritime spatial planning and production risk mitigation (Niyinyitoreye et al., 2025; Alemu & Zelalem, 2026). S1 (highly suitable), S2 (suitable), and N (unsuitable) zoning maps can be created using GIS methods based on the weights and scores of relevant environmental parameters, thereby supporting evidence-based operational decision-making and zoning policies (Gómez & Maynou, 2021; Nguyen et al., 2021). Comprehensive visualization of the biophysical conditions of the waters and more targeted coastal zone management to assist in policy formulation can be obtained by utilizing this technology (Kantor et al., 2024; Hou et al., 2025; Espinel et al., 2024). Although GIS-based site-selection technology and practices have been widely applied, research specifically analyzing the suitability of land for cultivating *K. alvarezii* in Tinangkung Village, Banggai Kepulauan Regency, is still limited. The unavailability of suitability zoning maps that integrate physical and chemical environmental parameters has resulted in farming management that is still general in nature and not based on scientific data.

Based on these conditions, a GIS-based spatial approach was used. The results of this study are expected to contribute scientifically in the form of a suitability zoning model and map that can be used as a spatial decision-support tool for sustainable mariculture planning in the coastal areas of Central Sulawesi. Therefore, this study aimed to assess the suitability of *K. alvarezii* farming sites in Tinangkung waters by adopting a GIS-based approach that incorporates key parameters (temperature, salinity, pH, DO, nitrate, phosphate, current, and brightness). This approach is expected to yield a scientific contribution in the form of a suitability zoning model and map that will serve as a spatial decision-support tool for sustainable mariculture planning in Central Sulawesi's coastal areas, focusing on ecosystem sustainability and enhancing the socio-economic resilience of coastal communities.

2. Materials and methods

2.1. Research Location and Sample Collection

This research was conducted in the seaweed farming coastal area of Tinangkung Village, South Tinangkung District, Banggai Islands Regency, Central Sulawesi Province, from May to August 2025. Geographically, this village is located in the Mansamat Bay area with coordinates 1°25'50.66"–1°25'55.17" S and 123°19'56.95"–123°19'19.12" E. The location was selected using purposive sampling based on the intensity of long-standing seaweed farming activities and its status as one of the production centers for *K. alvarezii* in Central Sulawesi. A total of 14 observation stations were established, representing the variation in water conditions in the study area (Mualam et al., 2022) and grouped into three main ecosystem zones based on physical characteristics and proximity to the coastline, namely the outer ecosystem zone (stations 1-4), the middle bay zone (stations 5-9), and the near-shore or estuary zone (stations10-14) (Huang et al., 2023; Arkema et al., 2024; Hunt et al., 2024).

2.2. Data Collection

The biophysical conditions of each station were measured in situ. The water quality parameters (physical and chemical) observed include temperature (°C), salinity (ppt), pH, dissolved oxygen/DO (mg L^{-1}), nitrate (mg L^{-1}), phosphate (mg L^{-1}), current velocity (m s^{-1}), and brightness (m). The weighting of each environmental parameter was determined based on literature-derived suitability criteria and previous studies on *Kappaphycus alvarezii* cultivation, as summarized in Table 1. Data collection was carried out through direct in situ field surveys, referring to the method proposed by Fahruddin et al. (2023). The quadrant transect method (50x50 cm) was used at 14 designated observation points. A water quality checker (multi-parameter probe) was used to measure temperature, salinity, pH, and DO, while a Secchi disk was used to measure brightness (Kurniawan et al., 2024; Lin et al., 2022). The determination of nitrate and phosphate concentrations was carried out using the spectrophotometry method according to APHA (Abimanyu et al., 2022; Mutiah et al., 2022). All parameters were then compared with the criteria for seaweed farming suitability based on relevant literature in the tropics. The classification of environmental suitability levels refers to the methods of Aris & Labenua (2020) and Adibrata et al. (2023), based on a suitability matrix of S1 (very suitable), S2 (suitable), and N (unsuitable), taking into account the tolerance limits of *K. alvarezii* to environmental conditions.

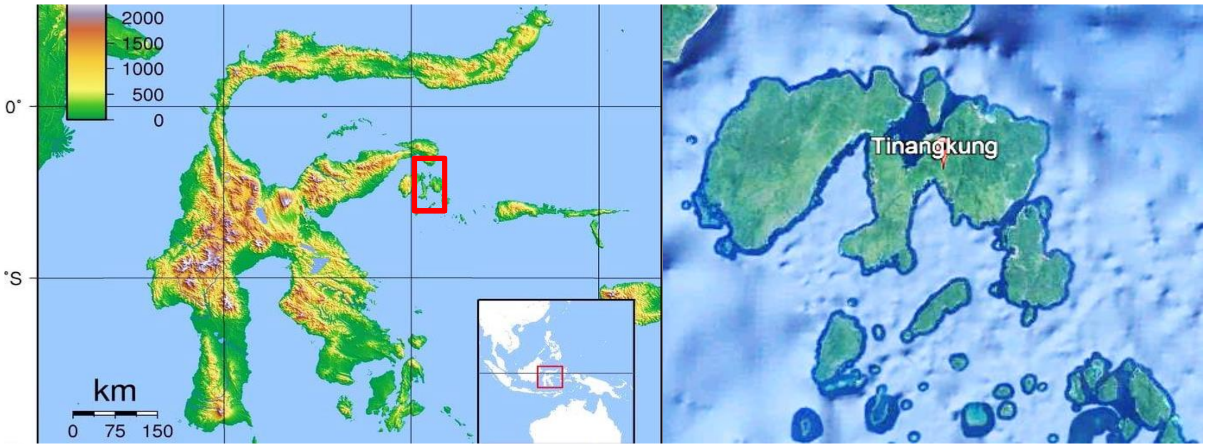

Figure 1. Location map of the study area in the waters of Tinangkung Village, Banggai Islands Regency, Central Sulawesi, Indonesia

2.3. Spatial Analysis

Geographic Information Systems (GIS) are used to perform spatial analysis. ArcGIS 10.8 GIS software includes administrative base maps, bathymetry, and interpolated water quality parameters. Each environmental parameter obtained is converted into a raster format through spatial interpolation (Inverse Distance Weighted – IDW) and scored based on the limiting factors that influence the growth of *K. alvarezii* (Pratiwy et al., 2023). To produce a zoning map for farming suitability, an overlay method was used to integrate various environmental parameters into a final thematic suitability map. The overlay was performed in layers, making it easier to identify areas that could be explored. The classification of the overlay results was divided into three classes: S1 (highly suitable), S2 (suitable), and N (unsuitable) (Khanyile, 2024; Banisalman & Elsharkawy, 2025).

2.4. Determination of Parameter Weights and Scores

The weight of each parameter is determined based on the sensitivity of *K. alvarezii* to environmental changes, referring to previous studies in tropical regions. The criteria and weightings are shown in Table 1.

2.5. Data Analysis

Data analysis was performed using descriptive quantitative averaging and compared with the suitability standards from relevant literature (Sihite et al., 2025). Next, the value of each parameter was normalized to a scale of 1 – 3, where a score of 3 = highly suitable (S1), 2 = suitable (S2), and 1 = unsuitable (N). The final suitability map was obtained through a raster overlay process using the equation (Adininggar et al., 2016):

$$S = \sum (Wi \times Xi)$$

where:
S = total suitability value,
Wi = weight of each parameter (%),
Xi = classification score for each parameter.

The final results of the spatial analysis were then classified into three suitability categories (S1, S2, and N) using the reclassification method. Since each parameter was scored on a scale of 1–3, the total suitability values ranged from 8 to 24. The classification thresholds were defined as follows: S1 (highly suitable): 19–24, S2 (moderately suitable): 13 –18, and N (not suitable): 8 –12. The class intervals were determined using equal interval classification.

3. Results and Discussions

The presentation of results follows a sequential approach, starting from the spatial distribution of individual water quality parameters, followed by their synthesis based on ecological zones, and culminating in the final suitability mapping.

Table 1. Weights and Range of Suitability Values for Each Environmental Parameter

Parameter	Weight (%)	Range S1 (Highly Suitable)	Range S2 (Suitable)	Range N (Unsuitable)	Reference
Depth (m)	15	2–15	>15	<2	Aris & Labenua (2020)
Salinity (ppt)	15	30–34	28–29	<28	Aris et al. (2021)
Temperature (^{0}C)	15	28–32	26–27 ; 33–34	<26 ; >34	Barillé et al. (2025)
Current velocity m s^{-1}	10	0.10–0.30	<0.10	>0.30	Mohiuddin et al. (2023)
Transparency (m)	10	>5	3–5	<3	Matos et al. (2024)
pH	10	7.5–8.5	6.5–7.4	<6.5; >8.5	Alamrousi et al. (2022)
DO (mg L^{-1})	10	>6	5–6	<5	Sihite et al. (2025)
Nitrate (mg L^{-1})	7	0.01–0.10	<0.01	>0.10	Abimanyu et al. (2022)
Phosphate (mg L^{-1})	8	0.05–0.30	<0.05	>0.30	Aris et al. (2021)

Table 2. Classification of Ecological Zones Based on Environmental Characteristics and Farming Suitability of *K. alvarezii* in Tinangkung Village

Ecosystem Zones	Station	General Characteristics	Zoning Category
Outside the Bay	1–4	High depth, high brightness & DO	Highly suitable (S1)
Middle Bay	5–9	Relatively stable parameters, moderate temperature & currents	Highly suitable (S1)
Near Coast/ Estuary	10–14	Low salinity & brightness, fluctuating pH	Suitable (S2) – some points close to N

Source: Processed data, 2025

3.1. The general conditions of the research location

Tinangkung Village is located in South Tinangkung Subdistrict, Banggai Islands Regency, Central Sulawesi Province. This area is a coastal region with geomorphological characteristics of an almost enclosed bay with stable shallow water. The farming area has an average depth of between 2.3 and 3.0 m, with the smallest area in the center of the bay reaching 26 m. The currents in this area are relatively calm and protected from large waves, providing ideal conditions for longline farming techniques. Barillé et al. (2025) reported that sheltered waters with shallow depths are very suitable for *K. alvarezii* farming, compared to open areas with stronger currents, as they reduce the risk of thallus fragmentation due to excessive hydrodynamic pressure. For a long time, the coastal community of Tinangkung has depended on seaweed farming, specifically the *K. alvarezii* variety. The socio-economic support of the Tinangkung coastal community, most of whom work as seaweed farmers, also strengthens the potential for developing this area as a center for sustainable farming. As Veenhof et al. (2024) emphasize the importance of community-based adaptation in facing coastal climate change, this social structure supports the idea of community-based management**.** To better interpret these spatial variations, the parameters were then analyzed collectively based on ecological zones.

3.2. Ecosystem Zones and General Characteristics

The 14 sampling points in Tinangkung Village were classified into three ecosystem zones based on depth, distance from the coast, and aquatic environmental conditions. This zoning represents the ecological gradation from sea to land, as presented in Table 2. Both the outer and middle bay zones were classified as highly suitable (S1). However, the outer bay is characterized by higher water depth, brightness, and dissolved oxygen, indicating more dynamic conditions. In contrast, the middle bay exhibits relatively more stable environmental parameters, particularly in terms of temperature and current. The outer bay zone is dominated by water with high currents and brightness, while the coastal zone has stronger terrestrial runoff, which causes changes in salinity and pH. Terrestrial runoff, also known as soil runoff, forms freshwater flows on the sea surface, which greatly affects coastal areas or estuaries. In addition to altering the distribution of pH and nutrients in the water, this process reduces salinity, increases turbidity, and reduces light penetration, which is an important component of seaweed photosynthesis (Ju et al., 2024; Dong et al., 2024). Conversely, areas outside the bay typically have stronger water circulation and higher water clarity, which supports nutrient exchange and oxygenation, creating an optimal environment for *K. alvarezii* farming (Ju et al., 2024). Classifying observation stations into coastal-mid-offshore ecological zones is a useful method for identifying spatial heterogeneity and creating more accurate farming suitability maps using GIS-based multi-criteria analysis (Mohamed et al., 2023; Li et al., 2024).

3.3. Water quality is based on ecosystem zones.

The Tinangkung waters have a relatively closed bay morphology with shallow waters in the center and along the coast. The water quality parameters based on ecosystem zones are presented in Table 3. The central region of the bay, based on spatial variation in environmental parameters, shows temperature, salinity, pH, and DO values that are close to the optimum range and suitable for *K. alvarezii* farming. In contrast, the coastal and estuary regions show lower salinity and higher turbidity levels due to the influence of land runoff. These conditions reinforce the potential of the central zone as a priority area for sustainable farming. It should be noted that the spatial maps (Figures 1–5) represent all sampling stations (St. 1–14), while the following discussion is structured based on ecological zones to facilitate interpretation.

Table 3. Water Quality Parameters Based on Ecological Zones in Tinangkung Village

Parameters	**Outer Bay Zone (St. 1–4)**	**Middle Bay Zone (St. 5–9)**	**Nearshore Zone (St. 10–14)**	**Optimal Range *K. alvarezii***	**Suitability Category**
Depth (m)	24.50 ± 0.30	10.34 ± 4.03	2.50 ± 5.48	1–10	S2–S3
Temperature (°C)	30.50 ± 0.08	30.10 ± 0.05	31.30 ± 0.08	27–31	S1–S2
Salinity (ppt)	30.10 ± 0.00	30.40 ± 0.00	29.00 ± 0.50	30–34	S1–S2
Transparency (m)	9.50 ± 0.89	6.50 ± 1.64	2.80 ± 0.00	>2	S1–S2
Current velocity (m/s)	0.30 ± 0.00	0.23 ± 0.00	0.20 ± 0.00	0.10–0.30	S1
pH	7.70 ± 0.04	7.50 ± 0.11	7.00 ± 0.20	6.50–8.50	S1–S2
Dissolved Oxygen (mg L^{-1})	7.70 ± 0.04	7.30 ± 0.13	6.90 ± 0.10	>5.0	S1
Phosphate (mg L^{-1})	0.13 ± 0.00	0.09 ± 0.00	0.12 ± 0.00	0.05–0.30	S1
Nitrate (mg L^{-1})	0.02 ± 0.00	0.02 ± 0.00	0.018 ± 0.00	0.008–0.10	S1

Source: Processed data, 2025

3.3.1. Outer Bay Zone (Stations 1–4)

Based on Table 3, water conditions in the outer bay zone show excellent physical and chemical stability with a brightness value of 9.5 m and DO of 7.7 mg/L. The temperature parameter of 30.5°C and salinity of 30.10 ppt are still within the ideal physiological range for the growth of *K. alvarezii* (27–31°C; 30–34 ppt). In addition, the current speed of 0.30 m/s allows for the supply of nutrients and oxygen without damaging the talus. The bathymetric map (Figure 2) shows water depths varying from 2 meters to more than 25 meters, with a pattern that deepens towards the south and southwest.

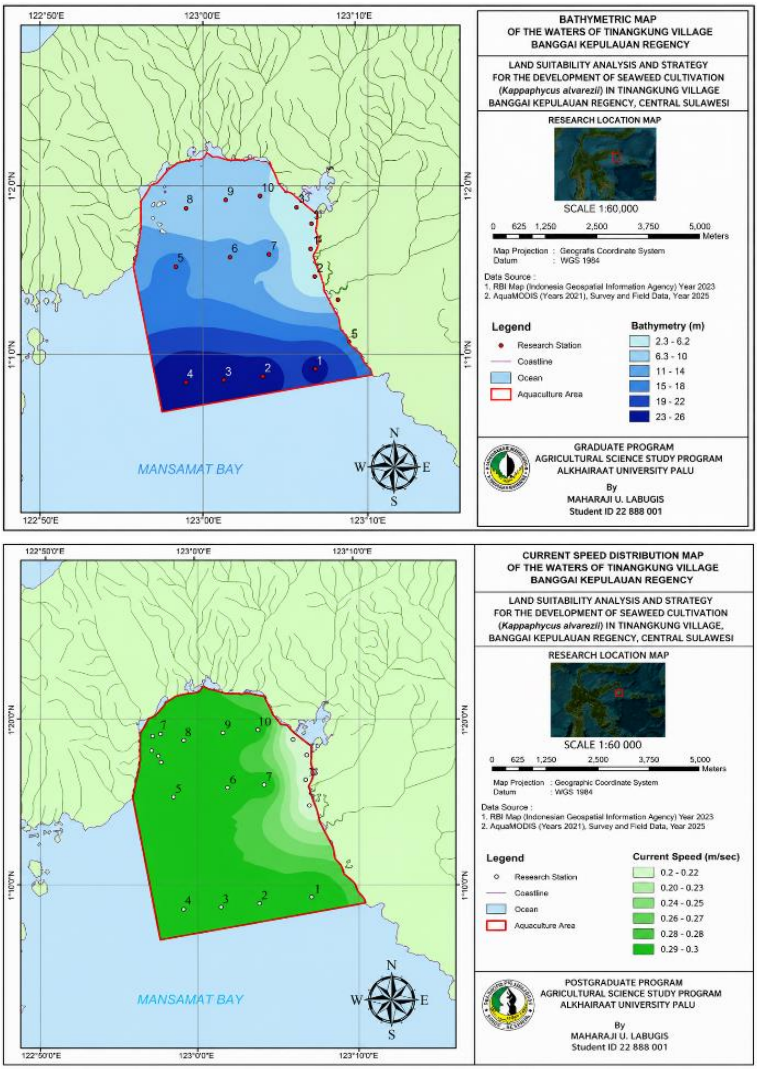

Figure 2. Map of Water Depth and Current Speed in the Waters of Tinangkung Village, Banggai Islands Regency

The area from the northern coast to the central part of the bay is relatively shallow (2–10 m), while the outer area reaches ≥ 20 m. This pattern indicates that the bay's bottom morphology is gentle in the inner part and becomes steeper towards the open sea. Each water quality parameter is first presented spatially to illustrate its distribution pattern across the study area.

The area between the central and southern parts of the bay on the Tinangkung coast, with depths ranging from 5 to 15 meters, is considered most suitable for sustainable seaweed farming. On the other hand, areas that are too shallow are susceptible to temperature changes and sedimentation, while areas that are too deep can limit the intensity of light needed for ideal photosynthesis.The water temperature on the Tinangkung coast ranges from 30.10°C to 31.2°C, with a spatial gradient pattern from the coast towards the open sea, as shown on the temperature distribution map (Figure 3). In the central to northern part of the bay, the temperature tends to be lower due to more active water circulation. In the south and east, which are relatively shallow, temperatures tend to be higher and receive greater exposure to solar radiation. The optimal temperature range for the growth of *K. alvarezii* seaweed is 28–32°C. Water temperature stability is one of the main factors determining the level of photosynthesis and growth rate of tropical macroalgae.

The salinity distribution map in Figure 3 shows salinity variations ranging from 28.1 to 30.3 ppt. The central to southern parts of the bay exhibit the highest salinity values, while the northern coast displays the lowest.

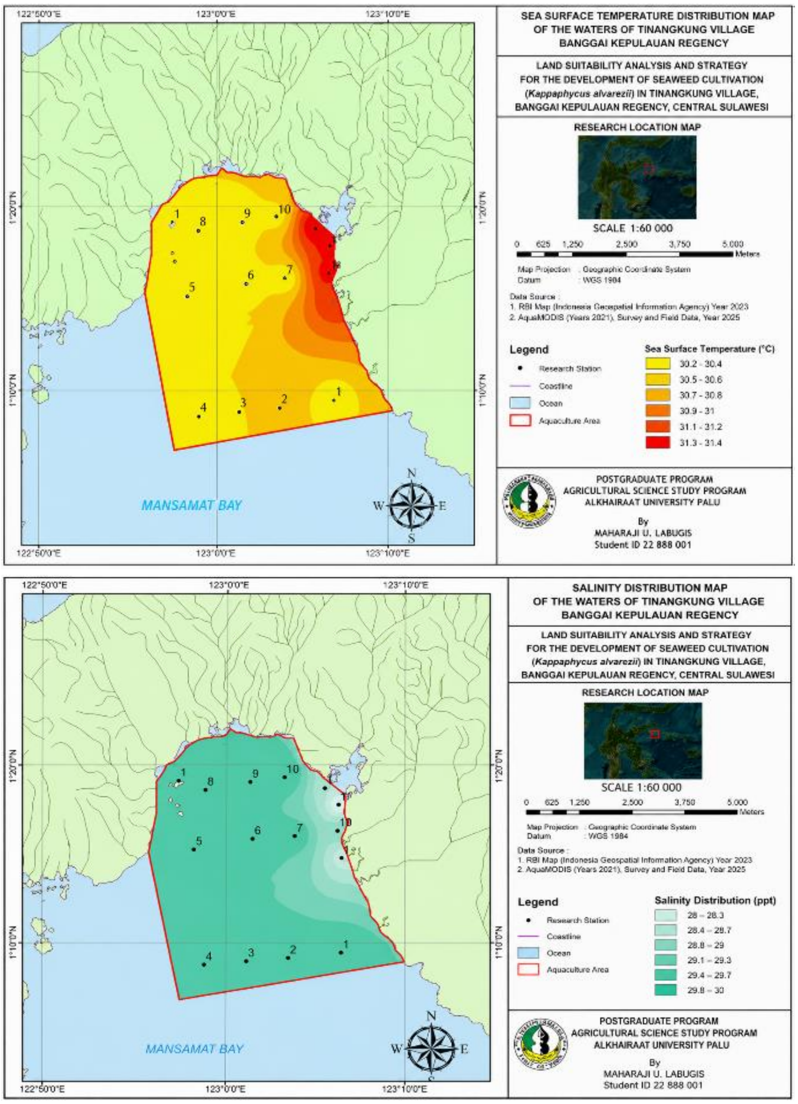

Figure 3. Map of Sea Surface Temperature and Salinity in the Waters of Tinangkung Village, Banggai Islands Regency

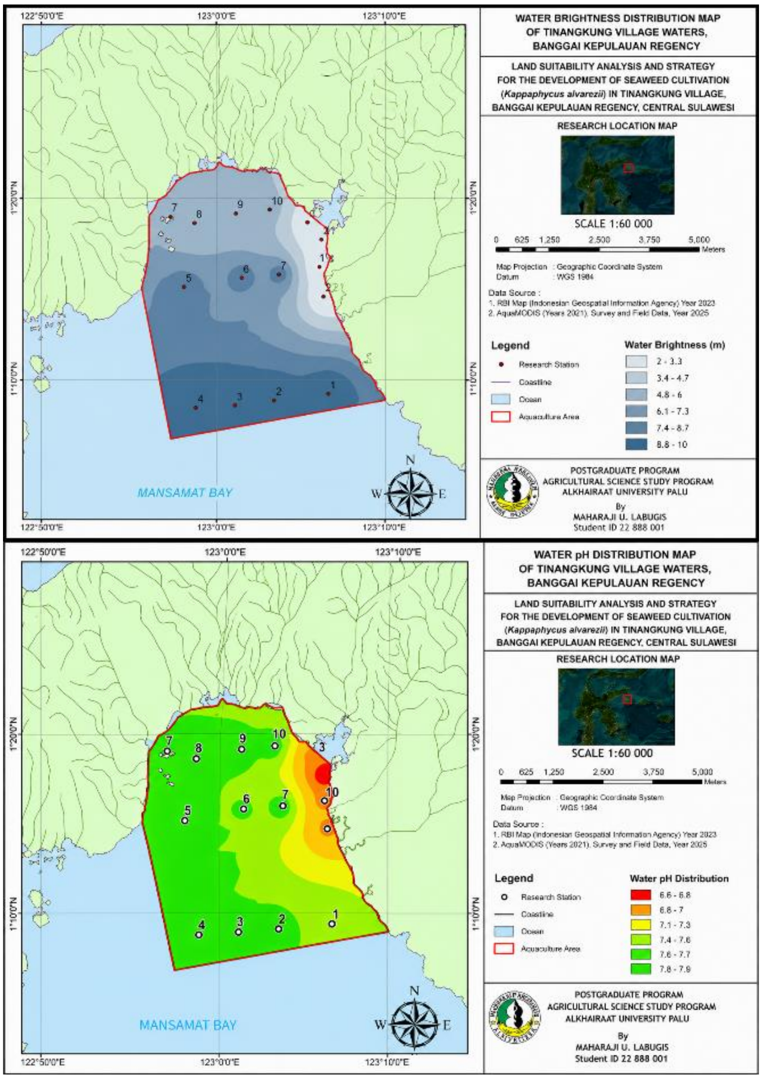

Figure 4. Map of Brightness and pH in the Waters of Tinangkung Village, Banggai Islands Regency

Land runoff, which carries fresh water, affects the decrease in salinity in areas near the estuary that occurs during high rainfall. Mohiuddin et al. (2023) reported that seaweed grows well at currents of 0.1–0.3 m/s and DO ≥ 6 mg/L. Furthermore, Khan et al. (2024) found similar results: that moderate current conditions can increase nutrient uptake and accelerate tissue regeneration. Therefore, we can conclude that this area is highly suitable (S1) for intensive seaweed farming. This spatial pattern indicates the environmental variability that influences seaweed water suitability.

3.3.2. Central Bay Zone (Stations 5–9)

The highest environmental stability was observed in the central bay zone at stations 5–9, with an average temperature of 30.3 °C, current velocity of 0.23 m/s, and pH of 7.5 (Table 2). Nitrate concentration of 0.025 mg/L and phosphate concentration of 0.09 mg/L indicate oligotrophic to mesotrophic water status with moderate fertility and no excess nutrients. This is considered ideal for the growth of *K. alvarezii* due to the balanced nutrient content. The average brightness value was 6.5 m, which is high enough to support the light penetration needed for photosynthesis. Figure 4 shows a map of brightness and pH of the coastal area in Tinangkung Village. The central and southern parts of the bay have high brightness (>6 m) and stable pH (7.4–7.8), while the coastal area is more turbid with slightly varying pH due to land runoff. Matos et al. (2024) suggest that waters with low turbidity and good light penetration can increase the photosynthetic efficiency of macroalgae and reduce the likelihood of sediment accumulation on the thallus surface. Thallus photosynthesis remains effective when brightness exceeds 5 m, accompanied by moderate current velocity. In the central and southern parts of the coastal area, there were relatively high levels of dissolved oxygen (6.8–7.8 mg/L) (Figure 5). On the other hand, coastal areas that receive terrestrial runoff have higher concentrations of phosphate and nitrate. Dissolved oxygen (DO) concentrations with values ≥ 7 mg/L indicate a productive water system with satisfactory oxygen exchange.

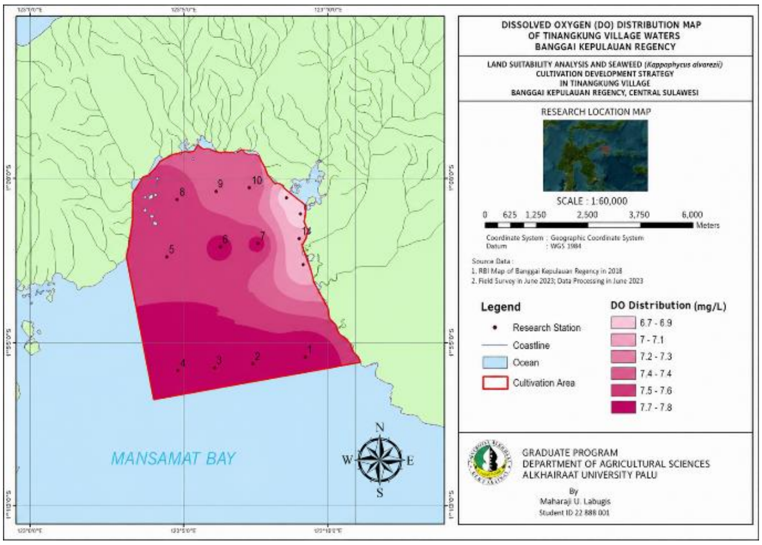

Figure 5. Map of Dissolved Oxygen (DO) Distribution in the Waters of Tinangkung Village, Banggai Islands Regency

The central zone of the bay is an area with a very high suitability rating (S1) for the sustainable farming of *K. alvarezii* due to a combination of stable temperatures, currents, moderate fertility, brightness, and dissolved oxygen (DO) concentrations. In line with Huang et al. (2023), the central transition zone of the bay typically has the most balanced hydrodynamic characteristics between the influences of the open sea and the estuary, making this area function as an "ecological optimum zone" for aquaculture activities and aquatic organisms.

3.3.3. Nearshore Zone/Estuary (Stations 10–14)

The distribution map of nitrate and phosphate in Figure 6 shows low to moderate concentration values. However, in coastal areas, land runoff causes slightly higher concentrations. Excessive nutrient levels cause eutrophication and reduce water quality, but this distribution is still considered safe and supports seaweed growth. Nitrate and phosphate concentrations indicate balanced oligotrophic to mesotrophic conditions (Aris et al., 2021). Compared to the other two zones, the coastal or estuary zone shows more active environmental conditions. In this area, the average brightness is 2.8 m, and salinity has decreased slightly to 29 ppt. Land runoff carries freshwater runoff and sediment particles from the catchment areas around the coast. The pH of 7.0 is still within a range suitable for growth. These conditions are consistent with the findings (Rasmussen et al., 2024), which explain that land runoff often causes waters near estuaries to experience a decrease in salinity and an increase in turbidity. However, *K. alvarezii* still tolerates salinity changes of 25-35 ppt and pH 6.5-8.5 without reaching a physiologically disruptive level. The coastal or estuarine areas are still considered suitable (S2) for seaweed farming, but better environmental management is needed, including organic waste control and routine water quality monitoring to ensure the sustainability of farming. These conditions indicate little anthropogenic pressure from household activities and organic runoff in the surrounding area. Alamrousi et al. (2022) stated that carrageenan quality and photosynthetic efficiency are affected by decreased pH and increased turbidity. Following the zonal analysis, all parameters were integrated using a spatial overlay approach to generate the final suitability map.

3.4. Spatial Map Analysis of Farming Water Suitability

The overall suitability of *K. Alvarezii* farming land is greatly influenced by the application of Geographic Information System (GIS) technology. To produce a land suitability zoning map, the physical and chemical parameters of the waters in each ecosystem zone were studied and integrated. Spatial analysis with thematic overlay helps to link environmental variability with coastal biophysical attributes (Wang et al., 2025). This method is in line with research conducted by (Zaniboni et al., 2024; Cook & Pétursson, 2025), which found that the combination of Multi-Criteria Decision Analysis (MCDA) and GIS can increase the accuracy of aquaculture site identification to more than 80%.Figure 6 shows a zoning map of *K. Alvarezii* farming suitability in the waters of Tinangkung Village, Banggai Kepulauan Regency, based on the integration results.

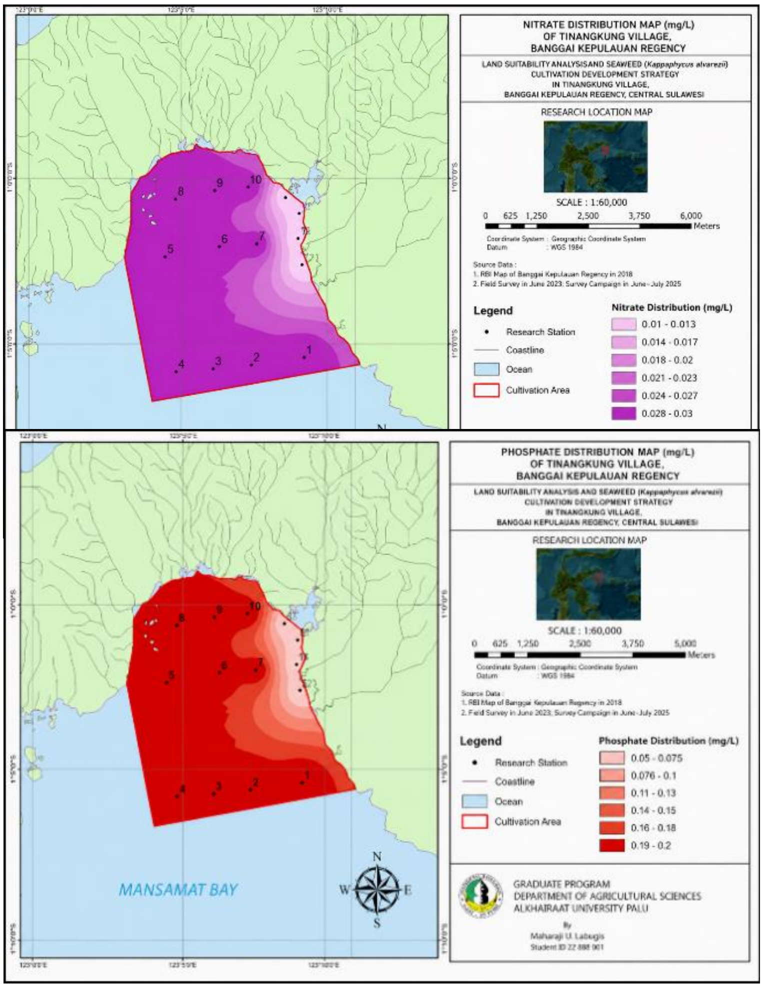

Figure 6. Map of Nitrate and Phosphate Distribution in the Waters of Tinangkung Village, Banggai Islands Regency

The results of spatial analysis based on Figure 7 show that Class S1 covers 722.79 ha (±31.8%) and is mostly located in the central and southern parts of the bay. This area produces high brightness levels (>6 m), stable current speeds (0.2-0.3 m/s), DO ≥7 mg/L, and constant salinity between 30 ppt and 31 ppt, creating an ideal environment for photosynthesis and thallus growth. In line with Muhammad et al. (2025), the suitability value for mariculture in China using the GIS and AHP approaches shows that zones with high suitability are dominated by areas with stable hydrochemical parameters. The S2 class category, covering an area of ±1,616.72 ha (66.6%), is located in the central to eastern regions. Conditions in this area are nearly ideal, with brightness between 3 and 5 meters and pH between 7.0 and 7.4. However, fluctuations in parameters such as pH and nitrate must be monitored, as they can affect productivity and carrageenan quality. Class N (±88.29 ha, ~3.6%) is located near the coast or estuary, characterized by high turbidity, salinity < 29 ppt, and pH changes due to land runoff.

Water depths of 5–15 meters also support sufficient light penetration for photosynthesis. Similarly, a decrease in salinity below 29 ppt and an increase in turbidity can inhibit light penetration and reduce photosynthetic efficiency (Li et al., 2024; Barillé et al., 2025). These conditions trigger osmotic stress and increase susceptibility to *ice-ice disease*, which commonly affects *K. alvarezii* in environments with high parameter fluctuations. The results of the study show that the characteristics of the aquatic ecosystem in Tinangkung Village are very conducive to the growth of *K. alvarezii*. For long-term development, priority should be given to the southern and central regions. Spatial zone-based management and location biosecurity are essential to reduce the risk of ice-ice disease, especially in the commercial seaweed industry (Mantri et al., 2024).

Vásquez Neyra et al. (2025) state that socioeconomically, GIS-based aquaculture zoning can increase production efficiency and reduce conflicts over marine space use.

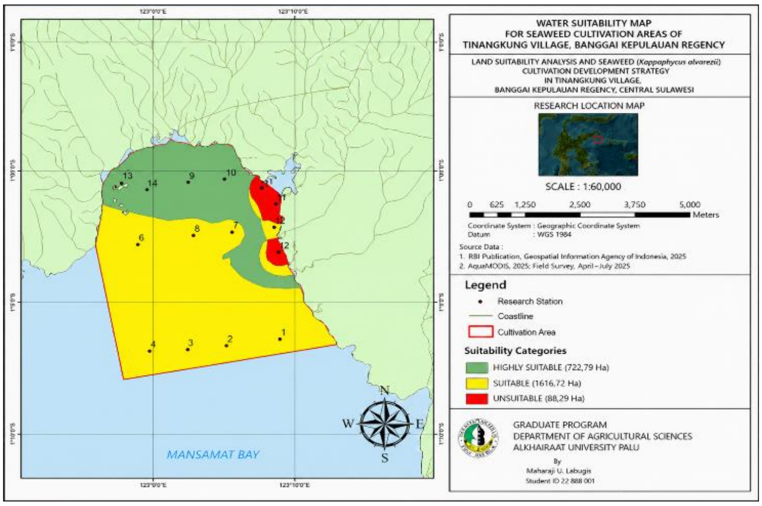

Figure 6. Map of Seaweed Farming Suitability Zonation in the Waters of Tinangkung Village, Banggai Islands Regency

A spatial approach to coastal food systems is essential for building community resilience to climate change. Physical and chemical parameters of the water are interrelated and influence seaweed growth. High DO values (6.9–7.7 mg L^{-1}) indicate adequate water circulation and optimal photosynthetic activity. Balanced nitrate and phosphate content indicates oligotrophic to mesotrophic conditions, which are suitable for seaweed growth without the risk of eutrophication. The physiological stability of the thallus is supported by the relatively constant salinity in the range of 30–31 ppt in the central part of the bay. These conditions indicate that nutrient balance and environmental parameter stability are prerequisites for the sustainable productivity of *K. alvarezii* farming. This final suitability map represents the combined influence of all environmental parameters and provides a basis for identifying priority areas for seaweed farming.

3.5. The spatial suitability model

The spatial suitability model of the environmental parameter overlay results shows that depth, salinity, and brightness are the main determinants of total suitability values. These three parameters contribute the highest weight in the spatial model (15% each). Areas with an optimal combination of these parameters form the S1 zone, which dominates the central and southern parts of the bay. This spatial pattern illustrates a typical suitability model for a semi-enclosed bay, where the transition zone between the open sea and the estuary is the area with the most balanced physical conditions.

3.6. Management implications

The findings of this study provide a scientific basis for sustainable coastal zone management in Banggai Kepulauan Regency. The resulting suitability zoning map serves as a decision-making tool for local governments and stakeholders in planning marine aquaculture development in highly suitable zones (S1), regulating planting cycles to mitigate ice-ice disease, and optimizing the use of marine space so that it does not overlap with other activities such as fishing, tourism, and transportation. Additionally, these results support improved environmental quality monitoring in coastal and estuarine areas with low suitability (S2–N). The GIS-based approach applied can also be replicated in other coastal areas as a basis for evidence-based management, thereby providing practical benefits for the development of productive, adaptive, and sustainable seaweed farming. Based on the suitability analysis, the central and outer bay zones are recommended as priority areas for seaweed farming development due to their stable environmental conditions, while coastal areas require additional management due to higher variability.

4. Conclusion

Spatial modeling based on Geographic Information Systems (GIS) is effectively used to assess the suitability of *Kappaphycus alvarezii* seaweed farming in the waters of Tinangkung, Central Sulawesi. The analysis results show three suitability classes, namely highly suitable (S1) covering an area of 772.79 ha, suitable (S2) 1,616.72 ha, and unsuitable (N) 88.29 ha. The central and southern zones of the bay are classified as the most suitable, with stable hydrodynamic conditions, high brightness, and salinity and depth that support optimal growth.Current stability and water quality are the main factors determining the productivity of *K. alvarezii* in semi-enclosed bays. The GIS-based suitability map provides basic information to support marine aquaculture zoning policies within the framework of the Banggai Islands Regency Marine Spatial Plan and can be used as a reference for efficient and sustainable mariculture planning in the coastal areas of Central Sulawesi.

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