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RESEARCH ARTICLE
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Delineation of Aquaculture Management Area (AMA) for *Kappaphycus alvarezii* through the Integration of GCOM-C Satellite Data and Aquatic Environmental Parameters on Tarakan Island

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ABSTRACT

Indonesia is the second-largest producer of *Kappaphycus alvarezii* seaweed in the world and is committed to the global sustainable development goals (SDGs). Tarakan Island is the northernmost large island in Indonesia, designated as a centre for *Kappaphycus alvarezii* production. The study of aquaculture management in the coastal zoning area of Tarakan Island is essential for supporting national development towards a sustainable concept. This research focuses on analyzing both ecological carrying capacity and production capacity during the western and eastern monsoons. Analysis and observation of aquatic environmental parameters were obtained in situ, consisting of nitrate, phosphate, dissolved oxygen, current patterns and velocities, salinity, pH, turbidity, brightness, sea surface temperature, tides, bathymetry, and substratum. The distribution of chlorophyll-a is derived from the satellite data from JAXA GCOM-C OCEAN CHLA V3. Modeling of carrying capacity evaluation using integrated assessment of aquatic ecological parameters. The results of the study showed a higher level of suitability in the west monsoon, with a suitable area of 6,211ha (53%) and a moderately suitable 5,503ha (47%). In the east monsoon, the suitable area was 4,511ha (38%), moderately suitable was 6,310ha (54%), and less suitable was 893ha (8%). The analysis of the aquaculture management area (AMA) estimates that effective carrying capacity and sustainability for the west monsoon covers 2,343ha, with a capacity of 5,903 longline units and a production capacity of 8,677.4 wet metric tons per cycle. For the east monsoon, the area encompasses 2,164ha, with a capacity of 5,452 longline units and a production capacity of 7,974.8 wet metric tons per cycle. The study results indicated that *Kappaphycus alvarezii* cultivation can be carried out throughout the year, in both the west and east monsoons

Keywords: Seaweed, GCOM-C, Monsoon, Sustainable, Site Selection

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INTRODUCTION

Aquaculture offers numerous potential social, environmental, and economic benefits, one of which is its contribution to the seaweed manifesto and various globally recognized Sustainable Development Goals (SDGs) (Cai et al., 2021). In Asia, the largest contributor to algae production is China, accounting for 60%, followed by Indonesia at 25%, the Republic of Korea at 5%, and the Philippines at 4% (FAO, 2024). Authorities have designated Tarakan Island, located in the northern region of the Unitary State of the Republic of Indonesia and bordering East Malaysia, for marine cultivation. Under North Kalimantan Provincial Regulation Number 14 of 2018,

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the east coast of Tarakan Island has been classified as a general use area for marine cultivation as part of the Coastal Area and Small Islands Zoning Plan, which is effective until 2038. Authorities have set aside an area of 11,714ha for the zoning improvement of traditional *Kappaphycus* (*K.*) *alvarezii* cultivation using the longline method. Statistical data on seaweed production in Tarakan City, North Kalimantan Province, in 2023 was around 201,998.12tons wet weight (KKP, 2024).

The success of sustainable *K. alvarezii* cultivation is highly dependent on the right water location, suitable physicochemical conditions, and the need for several inorganic nutrients, and the stability of primary productivity to support optimal algal growth (Sarjito et al., 2022). The distribution of nitrate and phosphate concentrations in tropical waters is a major limiting factor in the distribution and abundance of macroalgae (Basyuni et al., 2024). According to Price et al. (2015), chlorophyll-a functions as an indicator of primary productivity, water fertility, and the stability of the marine phytoplankton food web. The availability of sufficient chlorophyll-a in the waters will increase photosynthesis, which then triggers seaweed metabolism to absorb many nutrients (Zhang et al., 2024). The variation in nutrient content in seaweed is influenced by the type of seaweed species, age, monsoon conditions, light penetration adequacy, and the environmental water quality conditions (Lumbessy et al., 2020). Modelling chlorophyll-a in water bodies based on specialized satellite imagery such as JAXA GCOM-C OCEAN CHLA V3 has not been widely conducted; this imagery allows for the visualization of patterns on a broad spatial and temporal scale (Murakami, 2020). Isada et al. (2022) evaluated the precision of both the temporal and spatial distribution of chlorophyll-a in the waters by utilizing satellite data from GCOM-C for remote sensing needs in the coastal waters of Hokkaido, Japan.

This study combines monsoon patterns in the western and eastern regions to see how nitrate (NO_3) and phosphate (PO_4) are distributed or uses a special satellite to show how chlorophyll-a levels spread over a large area, along with other water quality factors, to help ensure that *K. alvarezii* can be sustainably farmed in coastal waters. Information from this study is important for all stakeholders as a way to identify problems early in the future, such as creating flexible zoning plans, crop rotation strategies, and regulating how many crops can be planted.

MATERIALS & METHODS

This research was conducted in the *K. alvarezii* seaweed cultivation zoning area in the coastal waters of Amal Beach, Tarakan Island, North Kalimantan Province, Republic of Indonesia (Fig. 1). Water quality samples were taken in situ and ex situ in early March 2024 for the west monsoon and late June 2024 for the east monsoon. Observation stations were established through stratified random sampling of 14 points, considering factors such as the active cultivation zone area, geomorphological characteristics, and the potential distribution of water currents. These locations were determined using Garmin GPS, with coordinates ranging from 30°16'9.137''~30°24'40.940''N and from 117°39'56.202''~117°42'40.858''E. Containers for storing seawater samples for nitrate, phosphate, and turbidity testing were specified according to BSN (2021), utilizing 250mL white polyethylene plastic bottles and 250mL Winkler glass bottles for dissolved oxygen testing. All bottle containers and sample caps were washed with a phosphate-free cleaner, rinsed with clean water, followed by a rinse with hydrochloric acid (HCl) in a 1:1 ratio, and then rinsed again with clean mineral-free water. This rinsing process was repeated three times before the bottles were dried.

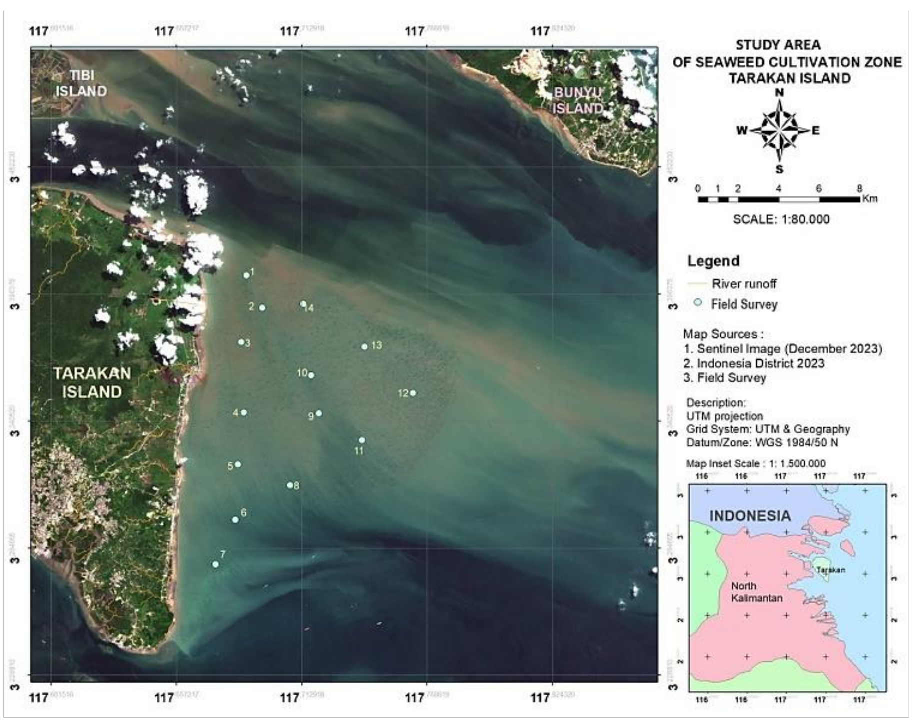

Fig. 1: Study Area of *Kappaphycus alvarezii* Seaweed Cultivation Zone.

Seawater samples were taken from the surface seawater column under partly cloudy weather conditions. The samples were rinsed three times, filled to capacity, sealed to prevent air bubbles, and then stored in a refrigerated cold box for laboratory analysis on the same day. Additionally, in situ measurements were taken, which included recording the sea surface temperature with a mercury thermometer, pH levels using a pH meter, salinity with a handheld refractometer, brightness using a Secchi disc, and surface water currents with an ocean current meter and compass. Phosphate concentrations were determined via a spectrophotometer at a wavelength of 880nm using ascorbic acid, while nitrate levels were assessed at 410nm with brucine sulphate; turbidity was measured with a nephelometer. Concurrently, seawater samples were collected to assess dissolved oxygen (DO) levels using a clean 250mL Winkler glass bottle, which was rinsed three times and filled completely. This sample was then mixed with 1mL of manganese (II) sulphate ($MnSO_4$) solution and 1mL of alkali iodide solution (kalium iodida) until a brown color developed. The bottle was subsequently sealed tightly and stored in a cold box for laboratory testing using the iodometric method.

Data Analysis

The chlorophyll-a value of ocean waters was based on satellite images that specifically measured chlorophyll-a, using data from JAXA GCOM-C OCEAN CHLA V3, which was accessed through the Google Earth Engine platform at https://earthengine.google.com. The script variables for the input image dataset included the daytime periods for the west monsoon, which spans from December 2023 to March 2024 and for the east monsoon, which spanned from May to September 2024; this was followed by geometry correction and atmospheric correction for cloud cover of less than 10% (Murakami, 2020). The configuration process for the horizontal visualization output of the chlorophyll-a image was obtained based on the average pixel value in the script dataset (Isada et al., 2022).

The creation of a research location map involved using Sentinel raster images, which were obtained in December 2023 and downloaded from the Google Earth Engine. Bathymetric data on sea depth was sourced from the Indonesian Geospatial Information Agency at: https://batnas.big.go.id/. This data was processed and configured in ArcGIS 10.3.1 software. The type of sediment substrate in situ, with visual observation and harmonic analysis of tidal conditions, referring to the water level at Malundung Port Tarakan, was obtained from the Indonesian Navy Hydro-Oceanography Centre. Microsoft Excel software processed this analysis using the Admiralty method.

Assessment of Seaweed Cultivation Area Suitability

The assessment of the suitability of cultivation zones *K. alvarezii* based on key water quality factors and weights refers to the literature review. The main variables affecting the growth of *K. alvarezii* got high scores and were organized according to Table 1 of the suitability matrix. The assessment of suitability levels was analyzed quantitatively as follows (Sarjito et al., 2022);

$$Y = \sum ai\ .Xn$$

The range of conformity levels is based on the equal interval method, following the equation:

$$I = \frac{(\sum ai.Xn)max - (\sum ai.Xn)min}{K}$$

Note : Y = The final value; ai = weight per variabel; Xn = suitability score; I = Interval of water suitability levels; K = number of suitability levels.

Then the interval of suitability levels is divided into 5 levels : highly suitable range 420~500, suitable range 340~420, moderately suitable range 260~340, less suitable range 180~260, and not suitable range 100~180. The spatial modelling algorithm integrates the scores for the water quality variable values, based on the matrix in Table 1.

$$SMA = (Nix20) + (Pix20) + (CSix15) + (WBix15) + (Tx10) + (Six10) + (ODix4) + (SSTix2) + (Chlix4) + (pHix2) + (DOx2)$$

Note: SMA = Suitability of Marine Waters; Nitrate level; Pi=Phosphate level; CS=Current speed level; WB=Water brightness level; T=Turbidity level; S=Salinity level; OD=Ocean deep; Chl=Chlorophyll-a; SST=Sea surface temperature level; pH=pH level; DO=Dissolved Oxygen.

Table 1: Matrix of 5 Levels of Suitability for *Kappaphycus alvarezii* Seaweed Cultivation

Variables	Level of Conformity (score)					Weight	Sources (Modification)
	HS (5)	S (4)	MS (3)	LS (2)	N (1)		
Nitrate (mg./L)	0.05~0.1	0.02~0.04	0.01 or >0.1	<0.01 or >0.5	>1	20	Simatupang et al. (2021); Sarjito et al. (2022); Syamsudin (2024);
Phosphate (mg/L)	0.05~0.1	0.02 ~ 0.04	0.01 or >0.2~1	<0.01 or >1	>2	20	Simatupang et al. (2021); Sarjito et al. (2022); Syamsudin (2024);
Current Speed (m/s)	25~30	20~24 or 31~40	15~19 or >40	<15 or > 45	<10 or >50	15	Sarjito et al. (2022); BSN (2022); Syamsudin (2024);
Brightness (m)	> 4	>3~ 4	2~3	>1~2	<1	15	Sulistiawati et al. (2020); Simatupang et al. (2021); Syamsudin (2024);
Turbidity (NTU)	< 5	5~10	>10~15	>15~20	> 20	8	Nurdin et al. (2023); Setiawan et al. (2023)
Salinity (mg/L)	28~31	26~27 or 32~33	25 or 34	23~24 or 36	<23 or >36	8	Simatupang et al. (2021); Madina et al. (2022); BSN (2022)
Depth (m)	3~10	2~<3 or 11~13	1~<2	>13~15	<1 or >15	4	Madina et al. (2022); BSN (2022)
Chlorophyll-a (mg/m^3)	>2.0~3.0	>1.0~2.0	>0.5~1.0	0.2~0.5	<0.2~3.0	4	Price et al. (2015) Alianto et al. (2020)
Sea Surface Temperature (°C)	28~30	24~27 or 31~ 32	22~23 or >32	21 or >34	<21 or >36	2	Simatupang et al. (2021); BSN (2022)
pH	7~8	6.5~7 or 8~8.5	6~6.4 or >8.5	4~6	<4 or >9	2	Simatupang et al. (2021); BSN (2022)
DO (mg/L)	>6	5~6	4~5	2~4	<2	2	Sulistiawati et al. (2020); Simatupang et al. (2021)

Note: HS: Highly suitable, S: suitable, MS: moderately suitable, LS: less suitable, and N: not suitable; Aquatic Productive Capacity and Production

Finally, the modelled data was laid out graphically and informatively using spline-based interpolation to classify the suitability of waters in the *K. alvarezii* cultivation zone using ArcGIS 10.3.1 software. This method is suitable for spatial data with small value variations. Spline basis interpolation generates high accuracy with minimal input data and predicts the maximum and minimum values based on the data stretching effect (Dmitriev and Ingtem, 2019). The equation followed is;

$$S_{(x,y)} = T_{(x,y)} + \sum_{i=1}^{n} \lambda_j \, R\,(r_j)$$

Note: j = 1; 2; ..., n; N represents the total number of points; λj = represents the coefficients of the linear equation; rj = represents the distance between the point (x, y) and point j; (x,y) and $R(r)$ are defined according to the selection method, which includes regular spline and tension spline.

Furthermore, effective utilization of the aquaculture management area within the cultivation unit necessitates an assessment of the capacity of the designated water area, which is classified as moderate or suitable. This assessment is crucial to ensure that the chosen location does not lead to social conflicts or ecological disruptions within the aquatic ecosystem and public access (Aguilar-Manjarrez et al., 2017; FAO, 2024). The seaweed cultivation unit utilizes the longline method as described in BSN (2011) & BSN (2022). It has dimensions of 50m by 50m, with a spacing of 1m between the ropes and 25cm between the seaweed seeds. For the distance and waterway route between construction units, the width of the route is set to be twice the length of the operational boats used by local farmers. The estimated optimal production capacity for cultivating *K. alvarezii,* utilizing an initial seed weight of 30g per bundle over 40 days, is expected to result in a biomass increase of four to six times (Barillé et al., 2025). Parakkasi et al. (2020) indicated that seaweed cultivation using the longline system can achieve a yield of up to five times the initial weight in 45 days.

RESULTS AND DISCUSSION

Based on the average bathymetric analysis, the study area's water depth contour was 5m (Fig. 2), and the beach slope was 1% (0.3°). Tides in Tarakan Island were characterized as mixed tides with a dominant semidiurnal pattern (Formzahl 0.25), occurring twice a day. This resulted in two high tides and two low tides each day, but the amplitude varied. The average tidal range was approximately 3.6m (360cm), while the average mean sea level (MSL) measured 1.8m (180cm) (Fig. 3). The characteristics of wind direction and speed in the waters of Tarakan Island predominantly blew from east to west, within the category of weak wind speed (12~20km/h) to moderate (21~29km/h). This resulted in a moderate wave height (H <1m) and a wave angle of 30° (Kahtijah et al., 2022). The data presented had minimal impact on coastal degradation and change, the coastal slope is smaller than 2%, and the position of this seaweed construction would remain submerged in the water column during the lowest tides of the mean sea level (Aguilar-Manjarrez et al., 2017). The wave height for *K. alvarezii* was a maximum of 1m (BSN, 2022).

Based on observations in the research area, the primary substrate of coastal waters was dominated by sand and muddy sand. Parakkasi et al. (2020) observed the daily growth rate of *K. alvarezii* longline for 45 days, showing that in seagrass substrates it was 2.39% (carrageenan 47.05%), coral 1.97% (carrageenan 44.76%), and sand 1.49% (carrageenan 53.24%). Nutritional factors around each growing substrate were considered to have played a sufficient role in meeting the growth needs of *K. alvarezii*. The research results in the study area indicated that the range of water quality varied for each parameter during both the west monsoon and east monsoon, as shown in Table 2. Each main and supporting water quality parameter would contribute to the growth of seaweed in each season (Manurung et al., 2021).

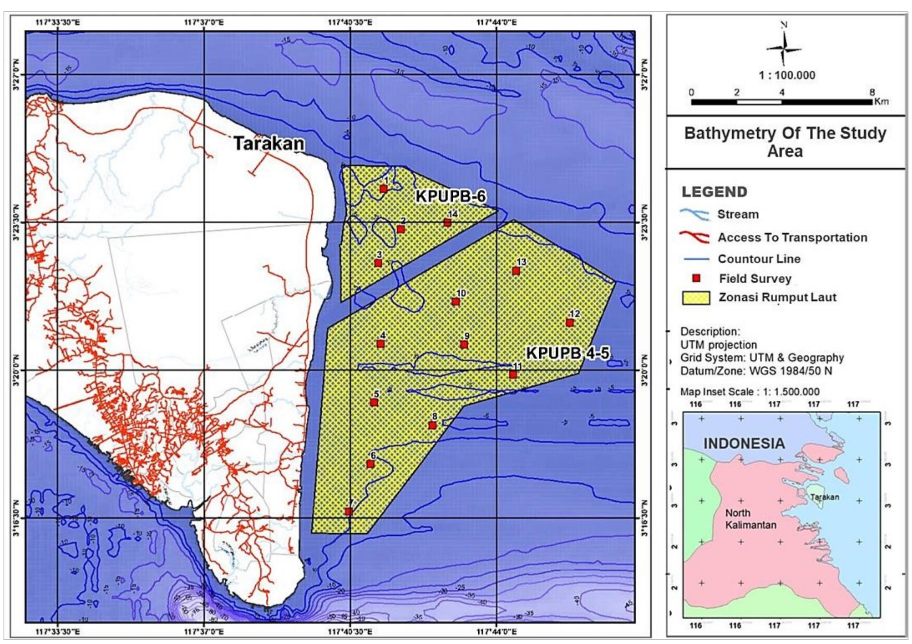

Fig. 2: Bathymetry of the Study Area.

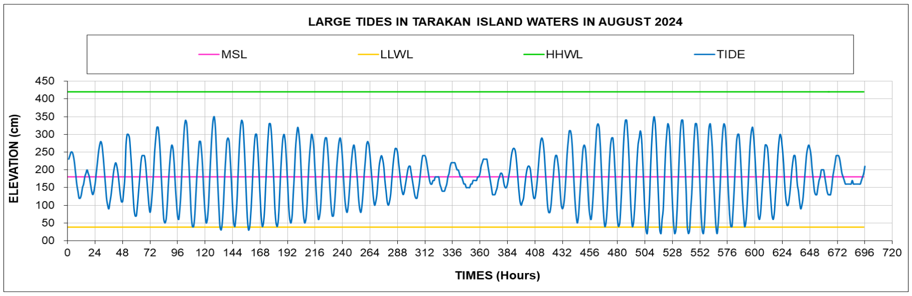

Fig. 3: Large Tides in Tarakan Island Waters in August 2024.

Table 2: Average Water Quality in the Seaweed Cultivation Study Area

Variables	West Monsoon Value		East Monsoon Value	
	Range	Mean±Sdev	Range	Mean±Sdev
Nitrate (mg/L)	0.09~0.19	0.13±0.03	0.12~0.36	0.18±0.06
Phosphate (mg/L)	0.004~0.083	0.036±0.033	0.001~0.075	0.020±0.023
Current Speed (m/s)	8~24	13.5±5.6	8~30	15.8±5.8
Brightness (m)	0.85~3.40	2.07±0.83	0.53~3.85	1.93±1.03
Turbidity (NTU)	1~15	5.9±5.2	1~16	4.9±5.2
Salinity (mg/L)	25~27	25.7±0.6	25~28	25.9±1.0
Depth (m)	3.3	3.3±0.0	3.3	3.3±0.0
Chlorophyll-a (mg/m^3)	0.50~0.85	0.69±0.13	0.60~1.10	0.90±0.15
Sea Surface Temperature (°C)	30~32	31.1±0.7	30~31	30.4±0.5
pH	7.0~8.6	8.0±0.3	7.2~8.5	7.6±0.3
DO (mg/L)	7.5~8.5	8.0±0.3	7.5~8.7	8.1±0.4

The distribution of nitrate concentration in waters ranged from 0.12~0.36mg/L (0.18±0.06) during the east monsoon and from 0.09~0.19mg/L (0.13±0.03) during the west monsoon. In contrast, phosphate concentration during the west monsoon ranged from 0.004~0.083mg/L (0.036±0.033), while it decreased to between 0.001~0.075mg/L (0.020±0.023) during the east monsoon. The distribution of the main variables indicated that nitrate concentration was classified as highly suitable to moderately suitable, whereas phosphate varied from highly suitable to less suitable (Fig. 4). Both phosphate (the main inorganic ion of phosphorus) and nitrate (the main inorganic ion of nitrogen) were limiting and essential factors for the growth of *K. alvarezii*; nitrate aided in the synthesis of structures and pigments, while phosphate supported energy metabolism and genetic material (Syamsuddin, 2024). A nitrate concentration range of 0.01~0.05mg/L and a phosphate range of 0.01~0.03mg/L were deemed sufficient to promote the growth of *K. alvarezii*. Research by Barillé et al. (2025), using a seed weight of 30g for 40 days in a long line, showed an average daily growth rate of 5.0% during the west monsoon at a nitrate range of 0.06~0.13, phosphate 0.02~0.06 and 3.3% during the east monsoon at a nitrate range of 0.03~0.10mg/L, phosphate 0.02-0.03mg/L. Previously, Maradhy et al. (2022) observed the range of nitrate, phosphate, and chlorophyll-a in the coastal waters of East Tarakan Island during the west monsoon (October/November), showing a range of 0.03~0.16mg/L; 0.11~0.17mg/L; and 0.13~3.24 mg/m^3.

The distribution of chlorophyll-a concentration in the waters of the research area was at a level suitable to moderately suitable for the growth of *K. alvarezii*. In the east monsoon, the concentration ranged from 0.60~1.10mg/m^3 (0.90±0.15), and in the west monsoon, it ranged from 0.50~0.85mg/m^3 (0.69±0.13). The distribution pattern of chlorophyll-a in the waters was influenced by the tidal currents in the Kayan Delta estuary, which flowed from the west and north of the Sembakung Delta towards Tarakan Island, carrying nutrients. This pattern diverged towards the southeast coast (Fig. 5). Chlorophyll-a serves as an indicator of primary productivity, water fertility, and the stability of the marine phytoplankton food web (Price et al., 2015). The distribution of chlorophyll-a in oligotrophic to mesotrophic waters indicated rich oxygen, the presence of nutrients, minimal algae blooms and minimal optimal brightness and turbidity levels (Alianto et al., 2020). Chlorophyll-a in waters was not a limiting factor, but the availability of chlorophyll-a in waters increased photosynthesis activity and triggered seaweed metabolism to absorb more nutrients (Zhang et al., 2024).

The range of surface water current speeds varied from unsuitable to suitable. During the east monsoon at 8~30cm/s (15.8±5.8), it predominantly flowed from the north to the south of the island. In contrast, during the west monsoon at 8~24cm/s (13.5±5.6), the current moved from the south to the north. According to Syamsudin (2024), a relatively higher current speed enhanced the efficiency of nutrient absorption, as it resulted in a thinner boundary layer, the space or layer between the nutrient-rich water and the seaweed thallus. An optimal current speed of 20~40cm was deemed ideal for both photosynthesis and nutrient absorption (including NH_4, CO_2, PO_4 and NO_3). This facilitated effective passive ion absorption, as well as the processes of osmosis and diffusion, alongside active absorption. Currents and waves played an important role in the circulation of nutrients and distribution of physical and chemical water quality (Sarjito et al., 2022). The optimal water current speed was 20~40cm/s (BSN, 2022).

Brightness levels ranged from unsuitable to suitable for seaweed growth in the west monsoon, with a range of 0.85~3.40m (2.07±0.83), and in the east monsoon, with a range of 0.53~3.85m (1.93±1.03). Kim et al. (2020) explained that increasing light penetration enhanced the primary production potential of aquatic systems, which in turn directly facilitated the growth of phytoplankton, seaweed, and other types of aquatic plants. The ideal level of brightness in coastal and marine waters supported the cultivation and growth of *K. alvarezii* in the 1~12m (Sulistiawati et al., 2020). The water turbidity levels were classified as less suitable, moderately suitable, and suitable for the cultivation of *K. alvarezii* during both the west monsoon and the east monsoon. The turbidity range during the west monsoon was 1~15NTU (5.9±5.2), while during the east monsoon, it was 1~16NTU (4.9±5.2). According to Nurdin et al. (2023), water turbidity had the

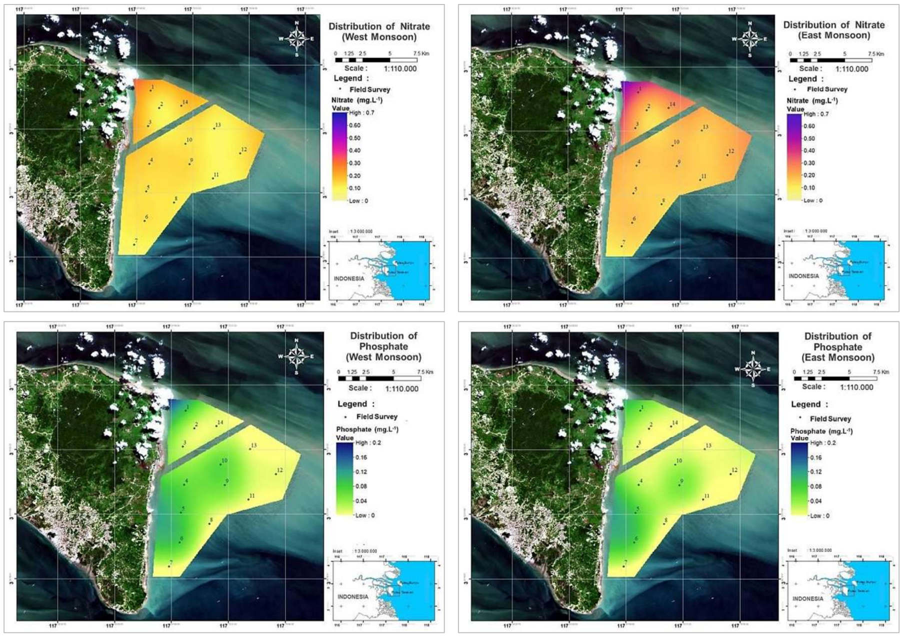

Fig. 4: Distribution of Main Nitrate and Phosphate Nutrients (West and East Monsoon).

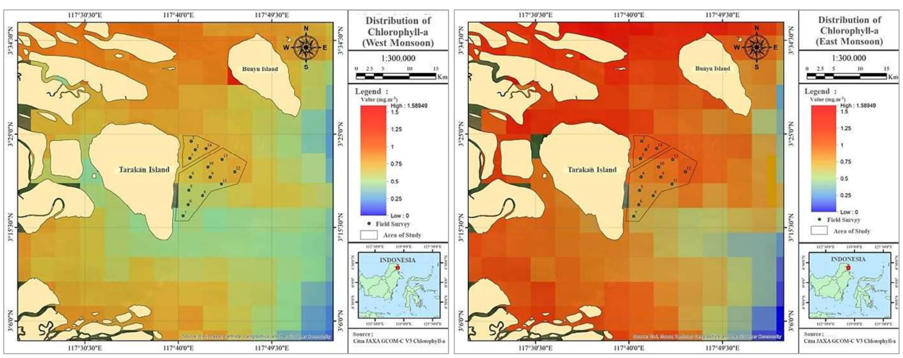

Fig. 5: Distribution of Chlorophyll-a (West and East Monsoon).

highest variability and could be a limiting factor for the growth of *K. alvarezii* if light penetration interfered with photosynthesis activity. Low light intensity will impacted the photosynthesis process and directly influenced the pigment content in *K. alvarezii*, such as phycobiliproteins (phycocyanin, phycoerythrin) and chlorophyll-a (Barillé et al., 2024; Zhang et al., 2024). Growing *K. alvarezii* using the long line method with a seed weight of 20g for 45 days resulted in an average daily growth rate of 5%, turbidity 7.49~7.72NTU (Setiawan et al., 2023). Barillé et al. (2025) research using 30g of seed for 40 days showed an average daily growth rate of 5.0% during the west monsoon at a turbidity range of 7.5~11.8NTU and 3.3% during the east monsoon at a range of 5.6~7.2NTU. The ideal turbidity level for *K. alvarezii* growth was <20NTU (Nurdin et al., 2023).

The range of water salinity was at a marginally suitable to very suitable level for seaweed growth, with measurements during the west season ranging 25~27mg/L (25.7±0.6) and during the east season ranging 25~28mg/L (25.9±1.0). High water salinity levels could impact the osmoregulation process in *K. alvarezii* cells, leading to suboptimal growth (Aris et al. 2021). Simatupang et al. (2021) suggested that an environment unsuitable for *K. alvarezii* could result in poor production or even failure, influenced by factors such as insufficient light, salinity levels dropping below 20mg/L, and elevated sea surface temperatures exceeding 35°C. These conditions might cause 'ice-ice' disease and promote the growth of undesirable plants on the thallus. According to BSN (2022), the ideal range of salinity in marine waters for cultivating *K. alvarezii* was 28~34mg/L. The sea depth based on the reading of the average bathymetric contour data was 5m, and after the difference with the average sea level, the range was 3.2m. Madina et al. (2022) noted that the optimal sea depth was in the range of 2~10m because it affected ecological conditions such as light, temperature, and currents that played a role in the growth of seaweed. The National Standardisation Agency (BSN, 2022) added the requirement for water depth for the cultivation of *K. alvaezii* of at least 2m at the lowest low water level (LLWL).

The range of sea surface temperatures in the research area tended to be warm in the west monsoon 30~32°C (31.7±0.7) and deacreased slightly in the east monsoon 30~31°C (30.4±0.5). All monsoons were highly suitable for *K. alvarezii*. Low light intensity, salinity <20mg/L, and high sea surface temperatures up to 35°C resulted in disease and failure of *K. alvarezii* cultivation (Simatupang et al., 2021). The National Standardisation Agency (BSN, 2022) has confirmed that the ideal water temperature range for *K. alvarezii* cultivation was in the range of 26°C~32°C. The pH level of the waters in the study area suitable for seaweed life during the west monsoon, ranged from 7.0~8.6 (8.0±0.3), and during the east monsoon, ranged from 7.2~8.5 (7.6±0.3). Simatupang et al. (2021) found that observations of water pH values at ten locations for the *K. alvarezii* production centre in Indonesia indicated a range of 7.5~8.5. The National Standardisation Agency (BSN, 2022) has confirmed that the ideal pH value range for *K. alvarezii* cultivation is 7~8.5. The range of dissolved oxygen concentrations was highly suitable for the life of *K. alvarezii*, both during the west monsoon, which measured from 7.5~8.5mg/L (8.0±0.3) and during the east monsoon, which ranged from 7.5~8.7mg/L (8.1±0.4). Observations of pH and dissolved oxygen at ten *K. alvarezii* production centre locations in Indonesia indicated a pH range of 7.5~8.5 and a dissolved oxygen range of 4.0~8.6mg/L (Simatupang et al., 2021).

Horizontal visual modelling of graphical image analysis for integrated assessments of aquatic ecological parameters showed that the suitability levels for the study area were better during the west monsoon (Fig. 6). Specifically, the area classified as suitable (S) was 6,211ha (53%), while the area considered moderately suitable (MS) was 5,503ha (47%). In contrast, during the east monsoon, the area classified as suitable (S) decreased to 4,511ha (38%), the moderately suitable area (MS) increased to 6,310 ha (54%), and there was a less suitable area (LS) of 893ha (8%) (Fig. 7).

This finding matched the study by Barillé et al. (2025), which indicated that growing *K. alvarezii* in South Sulawesi worked better in the western monsoon water (October/November). Specifically, the growth increased from 30g to 195g over 40 days, in contrast to the eastern season (July/August), where the increase was limited to 115g. According to Barille et al. (2025), this growth occurred when rainfall is high and the temperature was around 31.1±0.5, salinity 29.8±0.4, nitrate 0.07±0.01, phosphate 0.02±0.01, turbidity 8.9±2.6, pH 7.2±0.0, and current 0.06m/s. The spatial model of ecological suitability in the waters of the research area effectively represented seaweed life. A combination of suitable and fairly suitable areas could create potential effective zones for the sustainable cultivation of *K. alvarezii*. During the west monsoon, the potential effective area was classified as suitable and moderately suitable, measuring 11,714ha (100%). However, this area decreased to 10,821ha (92%) in the east monsoon.

Aquaculture management area (AMA) in water bodies designated as having sustainable suitability status was limited their utilization to no more than 20% of the total area. This approach was essential for maintaining the sustainability of *K. alvarezii* cultivation zoning activities, as it helped prevent social conflict, reduces waste, and minimizes ecological disturbances to aquatic ecosystems. Additionally, this limitation allowed for space for other forms of marine cultivation, supported the migration of biota, created buffer zones, and ensured public access (Aguilar-Manjarrez et al., 2017; FAO, 2024). The appropriate cultivation method for the research area was longline. According to the BSN guidelines (2022), each construction unit consists of a main rope measuring 50x50m. This design included 49 span ropes, spaced 1m apart. On each span rope, *K. alvarezii* seeds are tied 25cm

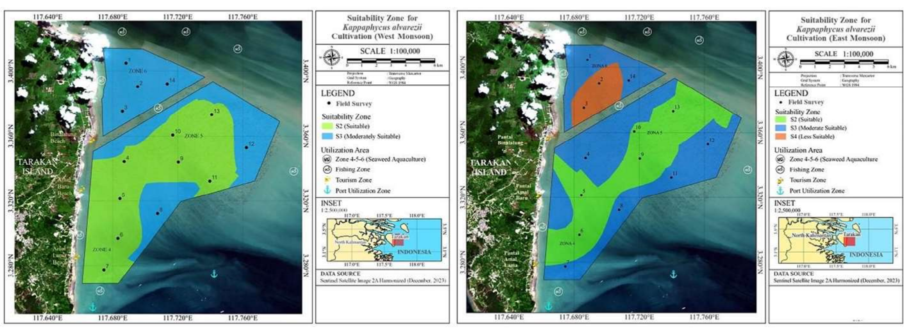

Fig. 6: Suitability of *Kappaphycus Alvarezii* Cultivation Zones (West and East Monsoon).

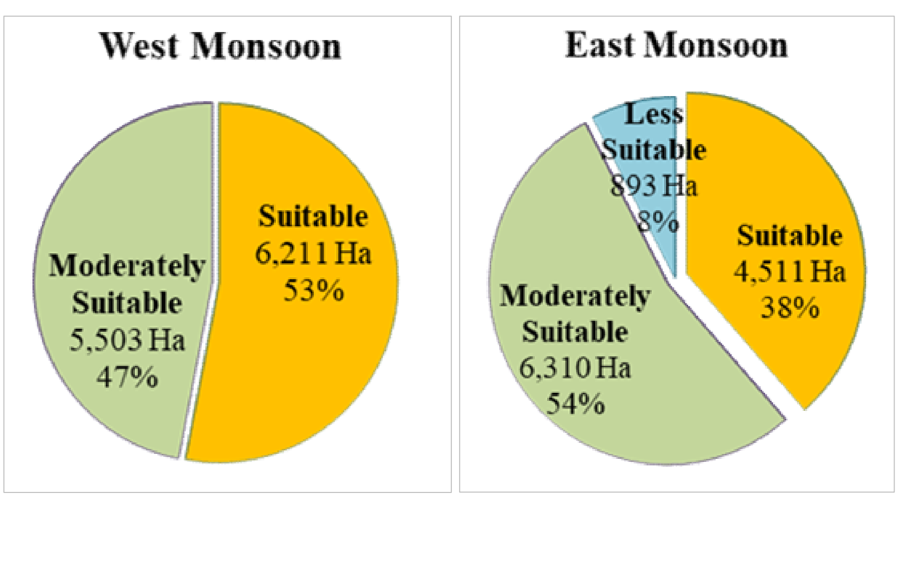

Fig. 7: Percentage of Potential Seaweed Cultivation Areas in the West and East Monsoon.

from one another so that each span rope contained around 200 bundles of seeds. In contrast, research conducted by Kamlasi et al. (2025) did not take into account the total width of the span rope in one construction unit, nor did it consider the daily operational transportation flow of farmers.

To ensure a smooth daily operational flow, the construction area dimensions, combined with the length of the boats used by local farmers, were approximately 13m. The analysis of the optimal production capacity for *K. alvarezii* cultivation was founded on an initial seed weight of 30g (Barillé et al. 2025) and a growth period of 45 days (Parakkasi et al. 2020). The analysis of the aquaculture management area (AMA) estimated that effective carrying capacity and sustainability for the west monsoon covers 2,343ha, with a capacity of 5,903 longline units and a production capacity of 8,677.4 wet metric tonnes per cycle. For the east monsoon, the area encompassed 2,164ha, with a capacity of 5,452 longline units and a production capacity of 7,974.8 wet metric tonnes per cycle.

Conclusion

The results of the study indicated that the marine aquaculture zoning area of Tarakan Island facilitated the cultivation of *Kappaphycus alvarezii*. An analysis of integrated studies regarding aquatic environmental parameters revealed a higher level of suitability during the west monsoon, with an area of 6,211ha classified as suitable (S) (53%) and 5,503ha as moderately suitable (MS) (47%). In contrast, during the east monsoon, the area classified as suitable (S) was 4,511ha (38%), moderately suitable (MS) was 6,310ha (54%), and less suitable (LS) amounted to 893ha (8%). The analysis of the aquaculture management area (AMA) estimated that effective carrying capacity and sustainability for the west monsoon covers 2,343ha, with a capacity of 5,903 longline units and a production capacity of 8,677.4 wet metric tons per cycle. For the east monsoon, the area encompassed 2,164ha, with a capacity of 5,452 longline units and a production capacity of 7,974.8 wet metric tons per cycle.

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Conflict of Interest: Authors declare there is no conflict of interest.

Data Availability: The data generated from this study are available from the corresponding author upon reasonable request, provided it will be used judiciously.

Ethics Statement: This research has obtained ethical approval from the Tarakan City Government, Republic of Indonesia, through the Agency for National Unity and Politics (Kesbangpol) concerning the scope of research activities for academic purposes.

Author's Contribution: JC contributed to the conceptual design of the study, as well as to data processing, analysis, and interpretation. SBP was responsible for the methodology, supervised the experimental procedures, and ensured the accuracy of the research results. D took part in gathering data, helped with data analysis, and confirmed that the analysis's findings were accurate. FP took part in reviewing the research manuscript, providing critical corrections and revisions to both the substance and editorial aspects of the study. All authors have reviewed and approved the final version of the research article manuscript.

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