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Spatial Multi-Criteria Evaluation for Sustainable Site Selection of *Kappaphycus alvarezii* Aquaculture in Bisa Island

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Abstract. This study aimed to evaluate the spatial suitability of coastal waters for *Kappaphycus alvarezii* aquaculture in Bisa Island, South Halmahera Regency, Indonesia, using a GIS-based Spatial Multi-Criteria Evaluation (MCE). Environmental parameters, including physical (water depth, transparency, current velocity, substrate type, and temperature), chemical (salinity, dissolved oxygen, pH, nitrate, and phosphate), and infrastructure factors (distance to harbor, distance to settlements, and labor availability), were analyzed and spatially integrated through a weighted overlay approach. The results indicate that the study area generally exhibits favorable environmental conditions for seaweed cultivation. The spatial suitability analysis shows that the total potential area reaches 458.88 ha, dominated by most suitable areas covering 403.02 ha, followed by moderately suitable areas of 55.86 ha. Physical and chemical parameters largely support optimal growth conditions, although phosphate concentration was identified as a limiting factor in certain locations. Infrastructure analysis revealed limited accessibility to harbors and settlements; however, this constraint is partially offset by high labor availability. Overall, the findings highlight the strong potential of Bisa Island for sustainable seaweed aquaculture development. The integration of GIS and multi-criteria decision analysis provides a robust framework for identifying optimal aquaculture sites and can support spatial planning and coastal resource management in tropical island ecosystems.

Keywords: *Seaweed aquaculture, Site suitability, GIS; Spatial multi-criteria evaluation, Kappaphycus alvarezii.*

INTRODUCTION

Indonesia is the world's largest archipelagic country, characterized by extensive coastal and marine ecosystems that support diverse ecological functions and economic activities. Coastal and marine waters account for more than two-thirds of the national territory, while the coastline stretches approximately 108,000 km, making coastal zones one of the most strategic natural resources for national development (Mejjad et al., 2022; Mitra et al., 2022). These ecosystems provide critical ecological services such as habitat provision, nutrient cycling, and coastal protection, while simultaneously supporting the livelihoods of millions of coastal communities through fisheries and aquaculture activities. Among the various aquaculture commodities, seaweed farming has emerged as one of the most promising subsectors due to its relatively low capital requirements, high export value, and its important role in improving the income and welfare of coastal households (Bakri et al., 2023).

Globally, the demand for seaweed-derived products has increased significantly in recent decades, particularly for hydrocolloids such as carrageenan used in food, pharmaceutical, and cosmetic industries. Indonesia has become one of the leading producers of tropical red seaweed, especially from the genus *Eucheuma* and *Kappaphycus*, which contribute substantially to the national fisheries export value (Basyuni et al., 2024). Among these species, *Kappaphycus alvarezii* is widely cultivated due to its high carrageenan content and strong market demand. However, the expansion of seaweed farming areas often occurs without adequate scientific consideration of environmental suitability. Physical and oceanographic conditions including water current, depth, transparency, and salinity play a crucial role in determining the productivity and survival of *K. alvarezii* cultivation (Yala and Sulistiawati, 2017). Failure to

account for these environmental characteristics may lead to reduced production yields and ecological degradation of coastal ecosystems, as reported in several seaweed farming centers in eastern Indonesia and Java (Hukom et al., 2020).

Halmahera Selatan Regency, located in the eastern Indonesian region of Maluku Utara, possesses extensive coastal waters that are most suitable for marine aquaculture development. One of the coastal areas with growing potential for seaweed cultivation is Bisa Island. In recent years, seaweed farming activities have gradually expanded in this region, driven by favorable environmental conditions and increasing market demand. Despite this development, the selection of farming sites has largely relied on traditional knowledge and empirical observations rather than systematic spatial analysis. As a result, farming areas may not always correspond to environmentally optimal locations, potentially reducing productivity and increasing ecological pressure on coastal ecosystems. Scientific assessments that consider environmental suitability are therefore essential to ensure that aquaculture expansion occurs in an efficient and sustainable manner (Achmad et al., 2020; Mustafa et al., 2022).

Land and water suitability evaluation plays a fundamental role in the early planning stages of aquaculture development. By identifying areas that meet optimal environmental criteria, suitability assessments can support the designation of productive farming zones and minimize ecological risks associated with poorly planned aquaculture expansion (Falconer et al., 2020; Mustafa et al., 2023). In coastal aquaculture planning, suitability analysis also contributes to spatial management by reducing conflicts between different coastal uses and promoting sustainable resource utilization. Consequently, integrating environmental assessment into aquaculture planning has become an important strategy for balancing economic development with ecosystem conservation.

Advances in geospatial technologies have significantly enhanced the capacity to evaluate aquaculture suitability at broader spatial scales. Geographic Information Systems (GIS) combined with Spatial Multi-Criteria Evaluation (MCE) provide powerful tools for integrating multiple environmental variables into spatial decision-making frameworks. These approaches allow researchers to synthesize diverse datasets such as oceanographic parameters, water quality indicators, and coastal geomorphology into a single spatial suitability index that identifies optimal farming locations (Hossain and Das, 2010; Palmer et al., 2021). The application of GIS-based suitability analysis has been widely adopted in aquaculture planning worldwide, supporting evidence-based site selection and environmental management. For example, spatial modeling approaches have been successfully applied to identify potential macroalgae cultivation zones along the Atlantic coast of France, providing insights into ecologically and economically suitable production areas (Medina-Madariaga et al., 2025).

Despite the increasing adoption of GIS-based aquaculture planning globally, spatial suitability assessments for seaweed farming remain limited in many Indonesian coastal regions, including Halmahera Selatan. In the case of Bisa Island, information regarding spatially explicit environmental suitability for *K. alvarezii* cultivation is still lacking. Meanwhile, increasing pressures on coastal resources arising from population growth, fisheries activities, and other coastal uses highlight the urgent need for comprehensive spatial planning approaches. Without scientifically informed site selection, the expansion of seaweed aquaculture may lead to inefficient resource use and potential ecological disturbances in coastal waters.

Therefore, this study aims to evaluate the spatial suitability of coastal waters for *K. alvarezii* seaweed farming in Bisa Island, South Halmahera Regency, Indonesia, using a GIS-based Spatial Multi-Criteria Evaluation approach. By integrating key environmental parameters into a spatial decision-support framework, this research seeks to identify potential cultivation

zones that support sustainable aquaculture development while optimizing the utilization of coastal resources. The findings are expected to provide valuable scientific input for regional coastal planning, aquaculture management, and sustainable seaweed industry development in eastern Indonesia.

METHODS

Study area

The study was conducted in the coastal waters of Bisa Island, located in North Obi District, South Halmahera Regency, North Maluku Province, Indonesia. The island lies within a tropical marine environment characterized by relatively clear coastal waters and favorable oceanographic conditions for seaweed cultivation. Geographically, the study area is located between approximately 1°16′–1°17′ S latitude and 127°41′–127°42′ E longitude. These coastal waters are influenced by monsoonal circulation patterns typical of eastern Indonesian seas and are widely utilized by local communities for small-scale fisheries and marine aquaculture activities. The selection of Bisa Island as the study area was motivated by its growing potential for seaweed aquaculture development, particularly for *K. alvarezii*. However, spatially explicit assessments of environmental suitability for seaweed cultivation in this region remain limited. Therefore, evaluating the spatial suitability of these waters is essential for guiding sustainable aquaculture expansion and coastal resource management.

Methodological framework

This study employed a GIS-based Spatial MCE framework integrated with the Analytic Hierarchy Process (AHP) to assess the suitability of coastal waters for *K. alvarezii* seaweed farming, following the approach of Orou-Seko and Adokiya (2026). The methodological workflow consisted of five main stages. First, relevant criteria and sub-criteria influencing seaweed aquaculture suitability were identified based on literature review, environmental conditions, and data availability. These criteria were structured hierarchically, consisting of an overall objective (site suitability), primary criteria groups (physical, chemical, and infrastructure factors), and corresponding sub-criteria. Second, spatial data were collected and processed to generate thematic layers representing each sub-criterion. All datasets were standardized into a common spatial format and resolution to ensure compatibility in the GIS environment. Each thematic layer was then prepared for suitability analysis. Third, all sub-criteria were reclassified into suitability classes using a three-tier system (not suitable, moderately suitable, most suitable). This step ensured comparability across heterogeneous environmental variables and enabled their integration into a unified spatial framework .

Fourth, the relative importance of each criterion and sub-criterion was determined using the AHP method through the construction of Pairwise Comparison Matrices (PCMs). Expert judgment was applied using a standardized nine-point importance scale to evaluate the relative influence of each factor. The resulting matrices were normalized to derive weights, ensuring that the total weight within each hierarchical level equals one. To ensure reliability, the consistency of the judgments was evaluated using a consistency ratio, and only acceptable levels of consistency were retained. Finally, all reclassified and weighted thematic layers were integrated using a weighted overlay approach within the GIS environment. In this process, each spatial unit (pixel) was assigned a suitability value based on the combination of its standardized score and corresponding weight. The integration was conducted hierarchically, first generating intermediate suitability maps for each criterion group, and subsequently combining them into a final spatial suitability map

Field data collection and laboratory analysis

Primary environmental data were collected through in-situ measurements at the nine observation stations. Physical parameters measured in the field included water depth, water transparency, current velocity, substrate type, and temperature. Water depth was measured using a measuring tape, while transparency was determined using a Secchi disk. Current velocity was measured with a current meter, and substrate type was visually identified through direct observation. Water temperature was measured using a multiparameter water quality checker.

Chemical parameters included salinity, dissolved oxygen (DO), pH, nitrate, and phosphate. Salinity, DO, and pH were measured directly in the field using the multiparameter water quality checker. Water samples (300 mL) were collected at each station and stored in pre-prepared sample bottles. The samples were preserved in a cool box during transportation and subsequently analyzed in the PT. Water Laboratory Nusantara (WLN) laboratory in Manado, North Sulawesi (N 1°29′27.43″; E 127°51′43.50″). Laboratory analysis was conducted to determine nitrate and phosphate concentrations.

Drone mapping, spatial data processing and GIS analysis

High-resolution aerial imagery of the study area was obtained using an unmanned aerial vehicle (UAV) or drone to generate detailed spatial information on coastal morphology and aquaculture areas. Drone imagery provides high spatial resolution data that enhances the accuracy of coastal mapping and spatial analysis compared to conventional satellite imagery. Additional spatial datasets were used to analyze infrastructural parameters such as distance to harbor and distance to settlements, which were calculated using spatial analysis tools in Google Earth and ArcGIS software. Labor availability was estimated based on demographic information obtained from relevant government agencies, including the Indonesian Ministry of Marine Affairs and Fisheries and the regional fisheries office. All spatial data were processed and analyzed using ArcGIS software, where spatial interpolation and overlay analysis were applied to generate thematic maps for each parameter.

Suitability sub-criteria thresholds

To construct the final spatial suitability model, all criteria were reclassified and assigned scores using a three-tiered categorical suitability scale (Table 1). This classification was informed by an extensive literature review and previous studies related to seaweed aquaculture site selection, ensuring that the suitability thresholds of each sub-criterion were adapted to the environmental conditions of the study area. The scoring system followed Orou-Seko and Adokiya, 2026, where a score of 1 represents not suitable, 2 indicates moderately suitable, and 3 denotes most suitable. Each parameter, including physical water conditions, chemical water quality, and infrastructure factors, was classified according to these suitability levels.

Subsequently, thematic spatial layers for each sub-criterion were generated and reclassified in ArcGIS using the defined thresholds. In the raster-based spatial model, each pixel was assigned a suitability score ranging from 1 to 3 based on its attribute values. For vector-based datasets, new attribute fields were created in the data tables, and the suitability scores were assigned to each corresponding spatial unit. This systematic reclassification process enabled the integration of all spatial criteria into the broader AHP-based spatial suitability analysis framework.

Table 1. Score and suitability rating of criteria used in the K. alvarezii aquaculture site selection

Criteria / Sub-Criteria	Not suitable (1)	Moderately suitable (2)	Most suitable (3)	Reference
Physical water parameters				
- Water depth (m)	<2 or >20	15–20	3–10	Adapted from Labenua and Aris (2021)
- Water transparency (m)	<1	1–2	>3	Adapted from Labenua and Aris (2021)
- Current velocity (m/s)	<0.1 or >0.4	0.1–<0.2 or >0.3–≤0.4	0.2–0.3	Adapted from Labenua and Aris (2021)
- Substrate type	Silt	Sand	Coral reef	Adapted from Yulianto et al. (2017)
- Water temperature (°C)	<25 or >35	25–<27 or >30–35	27–30	Adapted from Labenua and Aris (2021)
Chemical water parameters				
- Salinity (ppt)	<25 or >35	25–<32	32–35	Adapted from Labenua and Aris (2021)
- Dissolved oxygen (mg/L)	<4	4–6	>6	Adapted from Labenua and Aris (2021)
- pH	<7 or >9	>8.2–9	7–8.2	Adapted from Labenua and Aris (2021)
- Nitrate (mg/L)	<0.008 or >3.5	0.008–<0.1	0.1–3.5	Adapted from Labenua and Aris (2021)
- Phosphate (mg/L)	<0.02 or >2.0	>0.1–2.0	0.02–0.1	Adapted from Labenua and Aris (2021)
Infrastructure factors				
- Distance to harbor (km)	>10	1–10	<1	Adapted from Porporato et al. (2020)
- Distance to settlements (km)	>1.5	0.5–1.5	<0.5	Adapted from Yunis et al. (2020)
- Labor availability (Ind/km²)	<50	50–100	>100	Adapted from Hossain and Das (2010)

Weight importance determination

To determine the relative importance of each criterion and sub-criterion, Pairwise Comparison Matrices (PCMs) were constructed following the AHP framework proposed by Orou-Seko and Adokiya (2026). Each criterion was compared pairwise using a nine-point importance scale to express its relative significance in influencing seaweed aquaculture suitability. Expert-based judgments were used to assign comparison values, and the resulting matrices were normalized to derive priority weights for each criterion and sub-criterion. The weights were standardized such that their sum within each hierarchical level equals one, ensuring proportional contribution in the final model. To assess the reliability of the comparisons, a consistency check was performed by calculating the consistency ratio (CR). A CR value within an acceptable threshold indicates that the judgments are logically consistent and suitable for further analysis. Only matrices that met the acceptable consistency level were used to derive final weights.

Spatial suitability modelling

The reclassified thematic maps for each sub-criterion were integrated according to their respective hierarchical groups, namely physical water parameters, chemical water parameters, and infrastructure factors, using a weighted overlay method in ArcGIS, following Orou-Seko and Adokiya (2026). In this approach, each raster layer representing a sub-criterion was

multiplied by its corresponding weight, and all weighted layers were subsequently aggregated to produce composite suitability maps. The integration process was conducted hierarchically, where sub-criteria were first combined to generate suitability maps at the criterion level, and these intermediate outputs were further integrated to produce the final spatial suitability map. The resulting map represents the spatial distribution of suitability classes, where each pixel reflects the cumulative influence of all criteria based on their relative importance. This approach enables the identification of optimal locations for sustainable seaweed aquaculture development by incorporating both environmental and socio-economic considerations in a spatially explicit framework.

Model validation

Model validation was conducted to assess the reliability of the spatial suitability outputs. This process involved comparing the predicted suitable areas with existing seaweed farming locations in the study area. The model was considered valid if the majority of current cultivation sites were located within areas classified as suitable. Additionally, field verification was performed at selected sampling points representing different suitability classes to evaluate the agreement between model predictions and actual environmental conditions. This validation approach ensures the robustness and applicability of the spatial model for decision-making in aquaculture planning.

RESULTS

Environmental Characteristics of Coastal Waters

The measured environmental parameters (Table 2) indicated generally favorable conditions for *K. alvarezii* cultivation in the coastal waters of Bisa Island. Water depth ranged from 0.4 to 5.06 m, while water transparency exhibited a similar range (0.4–5.06 m). Current velocity varied between 0.1 and 0.3 m/s, reflecting moderate hydrodynamic conditions. Substrate types were dominated by coral reefs and sandy bottoms, and water temperature ranged from 26.28 to 27.53°C. In terms of water quality, salinity ranged from 29 to 33 ppt, DO from 8.86 to 13.59 mg/L, and pH from 5.62 to 9.97. Nutrient concentrations showed nitrate levels below 0.5 mg/L and phosphate ranging from 0.006 to 0.009 mg/L. Overall, these conditions suggest that the study area provides a generally suitable marine environment, although some parameters exhibit variability that may influence spatial suitability.

Table 2. Environmental characteristics of coastal waters in Bisa Island

Parameter	Observed Range	Optimal Range	Reference
Water depth (m)	0.4–5.06	3–10	Labenua and Aris (2021)
Water transparency (m)	0.4–5.06	>3	Labenua and Aris (2021)
Current velocity (m/s)	0.1–0.3	0.2–0.3	Labenua and Aris (2021)
Substrate type	Coral reef, sand	Coral reef	Yulianto et al. (2017)
Temperature (°C)	26.28–27.53	27–30	Labenua and Aris (2021)
Salinity (ppt)	29–33	32–35	Labenua and Aris (2021)
Dissolved oxygen (mg/L)	8.86–13.59	>6	Labenua and Aris (2021)
pH	5.62–9.97	7–8.2	Labenua and Aris (2021)
Nitrate (mg/L)	<0.5	0.1–3.5	Labenua and Aris (2021)
Phosphate (mg/L)	0.006–0.009	0.02–0.1	Labenua and Aris (2021)

Spatial Distribution and Suitability of Physical Parameters

The spatial analysis of physical parameters revealed varying levels of suitability across the study area (Figure 1). Water depth showed a substantial proportion of not suitable areas (72.80%; 334.04 ha), while most suitable areas covered 27.20% (124.84 ha). Water transparency was predominantly classified as moderately suitable (55.76%; 255.89 ha), with

the remaining area categorized as not suitable (44.24%; 202.99 ha). Current velocity and temperature exhibited relatively homogeneous conditions, with the entire study area classified as moderately suitable (100%; 458.88 ha). Substrate suitability was more heterogeneous, consisting of moderately suitable areas (49.46%; 226.94 ha) and most suitable areas (49.31%; 226.26 ha), with only a small proportion classified as not suitable (1.24%; 5.68 ha). The integrated physical suitability map indicated that moderately suitable areas dominated the region (54.74%; 251.19 ha), followed by most suitable areas (32.41%; 148.73 ha) and a smaller proportion of not suitable areas (12.85%; 58.96 ha).

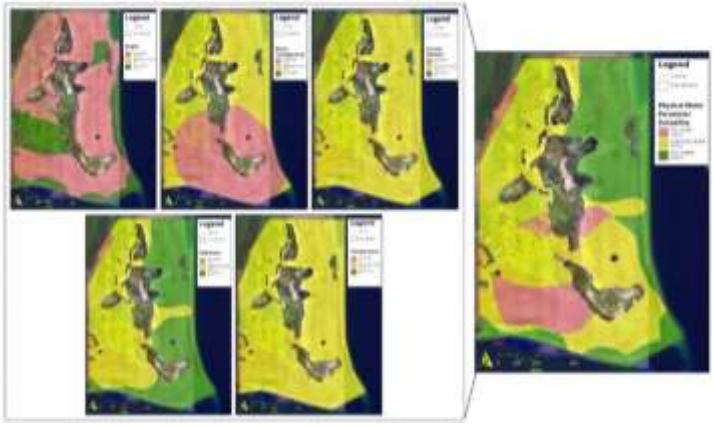


Figure 1. Spatial distribution and suitability maps of physical parameters in the coastal waters of Bisa Island, including water depth, water transparency, current velocity, substrate type, and water temperature, along with the integrated physical suitability map for seaweed aquaculture (458.88 ha).

Spatial Distribution and Suitability of Chemical Parameters

The spatial distribution of chemical parameters generally indicated favorable water quality conditions for seaweed aquaculture (Figure 2). Salinity was predominantly classified as moderately suitable (95.41%; 437.81 ha), with a smaller portion categorized as most suitable (4.59%; 21.07 ha). Dissolved oxygen, pH, and nitrate levels demonstrated optimal conditions, with the entire study area classified as most suitable (100%; 458.88 ha). In contrast, phosphate concentration emerged as a limiting factor, with a substantial portion of the study area classified as not suitable (74.76%; 343.05 ha), while most suitable areas covered 25.24% (115.83 ha). The integrated chemical suitability map showed that moderately suitable areas dominated (70.17%; 321.99 ha), followed by most suitable areas (29.83%; 136.89 ha).

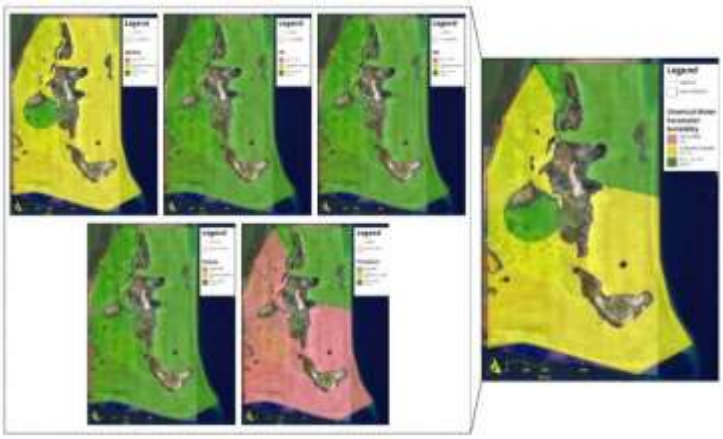


Figure 2. Spatial distribution and suitability maps of chemical parameters in the coastal waters of Bisa Island, including salinity, dissolved oxygen (DO), pH, nitrate, and phosphate, together with the integrated chemical suitability map for seaweed aquaculture (458.88 ha).

Infrastructure Suitability Analysis

The analysis of infrastructure-related parameters revealed contrasting conditions (Figure 3). The study area was classified as not suitable in terms of distance to harbor and settlements, covering the entire area (100%; 458.88 ha), due to distances exceeding optimal thresholds. In contrast, labor availability was classified as most suitable across the entire study area (100%; 458.88 ha), reflecting strong human resource capacity for aquaculture development. As a result, the overall infrastructure suitability was classified as not suitable (100%; 458.88 ha), indicating that logistical accessibility remains a key constraint, although partially offset by the availability of labor.

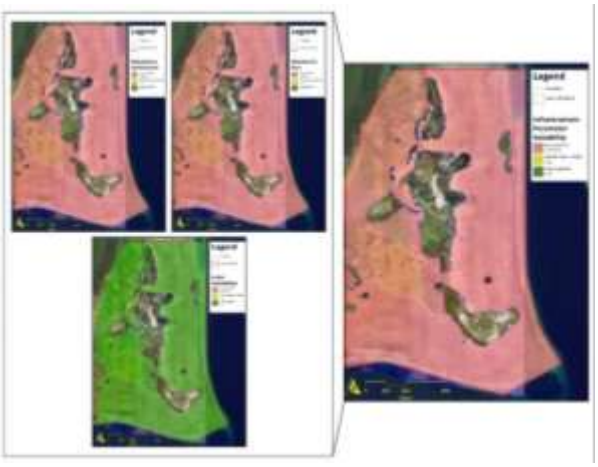


Figure 3. Spatial suitability maps of infrastructure-related parameters in the coastal waters of Bisa Island, including distance to harbor, distance to settlements, and labor availability, along with the integrated infrastructure suitability map (458.88 ha).

Final Spatial Suitability for Seaweed Aquaculture

The final spatial suitability model, integrating physical, chemical, and infrastructure parameters using a weighted overlay approach, revealed that the majority of the study area is most suitable for *Kappaphycus alvarezii* cultivation (Figure 4). Most suitable areas covered 87.83% (403.02 ha), representing the dominant suitability class, while moderately suitable areas accounted for 12.17% (55.86 ha). These findings indicate a strong potential for sustainable expansion of seaweed aquaculture in the coastal waters of Bisa Island, supported by generally favorable environmental conditions despite certain infrastructural limitations.



Figure 4. Final spatial suitability map for *K. alvarezii* seaweed aquaculture in the coastal waters of Bisa Island, Indonesia (458.88 ha).

DISCUSSION

The success of seaweed aquaculture development is strongly influenced by environmental conditions, including physical and chemical water parameters, as well as supporting infrastructure. Previous studies have emphasized that the interaction among these components determines productivity levels and the sustainability of seaweed farming systems in coastal environments (Hossain and Das, 2010; Yulianto et al., 2017; Porporato et al., 2020; Yunis et al., 2020; Labenua and Aris, 2021). In this study, the integration of these parameters through a spatial multi-criteria evaluation framework revealed that the coastal waters of Bisa Island generally provide favorable conditions for *K. alvarezii* cultivation.

Physical parameters play a critical role in shaping habitat suitability and directly influence the physiological performance of seaweed. Water depth in the study area ranged from 0.4 to 5.06 m, which falls within the commonly recommended range for seaweed farming practices. Such shallow to moderate depths allow sufficient light penetration to support photosynthesis, while maintaining environmental stability (Pong-Masak and Sarira, 2020; Momo et al., 2024). Depth is widely recognized as a key determinant of seaweed productivity, as excessively shallow waters may expose organisms to environmental stress, whereas deeper waters may limit light availability (Ullah et al., 2023). The relatively consistent depth conditions observed in this study suggest a stable environment conducive to optimal growth.

Water transparency is another essential factor influencing light availability within the water column. The observed transparency range (0.4–5.06 m) indicates generally adequate light penetration to sustain photosynthetic activity. Transparency has been identified as a key driver of energy availability for marine primary producers (Yuniarsih et al., 2015). Although optimal transparency values for seaweed growth are often reported at lower ranges (0.3–1.0 m), cultivation can still be effective in clearer waters as long as sufficient light reaches the cultivation depth (Ullah et al., 2023). Therefore, the transparency conditions in the study area are considered supportive of sustained biomass production.

Hydrodynamic conditions, represented by current velocity, were within the range of 0.1–0.3 m/s, which is widely regarded as optimal for *K. alvarezii* cultivation. Water movement facilitates nutrient exchange, enhances oxygen distribution, and prevents sediment accumulation on the thallus surface (Ihsan et al., 2021). Previous studies have suggested that current velocities between 0.1 and 0.4 m/s provide an optimal balance between nutrient supply and physical stability of seaweed structures (Manurung et al., 2021). The relatively uniform current conditions observed in this study indicate a hydrodynamic environment that supports efficient nutrient transport without causing mechanical stress.

Substrate characteristics also contribute significantly to cultivation success. The dominance of coral reef and sandy substrates indicates a generally favorable seabed condition. Coral substrates provide stable attachment surfaces and are associated with higher survival rates and biomass production (Waang et al., 2024), whereas sandy substrates, although less stable, can still support growth under suitable hydrodynamic conditions (Parakkasi et al., 2020). The coexistence of these substrate types suggests that the study area offers a balanced physical environment for seaweed farming.

Temperature conditions ranged from 26.28 to 27.53°C, which falls within the optimal range for tropical seaweed growth. Temperature directly affects metabolic processes, nutrient uptake efficiency, and growth rates (Ullah et al., 2023). Stable thermal conditions, as observed in this study, are particularly important in maintaining consistent production levels. Previous findings have indicated that optimal temperature ranges for seaweed growth generally fall between 25 and 30°C (Lideman et al., 2013), further confirming the suitability of the study area.

Chemical parameters further reinforce the suitability of the study area. Salinity levels (29–33 ppt) fall within the optimal tolerance range for most commercially cultivated seaweed species, supporting physiological stability and nutrient uptake processes (Ullah et al., 2023; Abdullah et al., 2020). Similarly, dissolved oxygen concentrations (8.86–13.59 mg/L) were well above the minimum threshold required for metabolic activities, indicating highly favorable conditions for respiration and ecosystem functioning. Adequate dissolved oxygen levels are essential for maintaining healthy growth and preventing physiological stress (Ullah et al., 2023).

The pH range (5.62–9.97) indicates spatial variability in water chemistry, likely influenced by biological activity and local oceanographic processes. While optimal pH for seaweed growth is generally reported between 7.5 and 8.5 (Ullah et al., 2023), the majority of the study area remained within acceptable ecological limits (Abdullah et al., 2020), suggesting that pH does not pose a significant constraint overall. In contrast, nutrient availability particularly phosphate emerged as a limiting factor. While nitrate concentrations (<0.5 mg/L) remained within acceptable ranges for seaweed growth, phosphate concentrations (0.006–0.009 mg/L) were below the commonly reported optimal levels (Simatupang et al., 2021). This indicates that the study area may exhibit oligotrophic characteristics, where nutrient availability is relatively low. Despite this limitation, seaweed species such as *K. alvarezii* are known for their efficient nutrient uptake mechanisms, allowing them to grow under nutrient-limited conditions. However, prolonged nutrient limitation could potentially affect long-term productivity and biomass yield.

Infrastructure factors present a contrasting perspective. Although the study area was classified as not suitable in terms of distance to harbor and settlements based on established thresholds, the actual distances (12.88 km to harbor and 5.96 km to settlements) still allow for functional accessibility. Previous studies have highlighted the importance of infrastructure in supporting production efficiency and market connectivity (Noriega, 2024; Ross et al., 2025). Additionally, proximity to population centers facilitates labor availability and local market access (Falconer et al., 2016; Yunis et al., 2020). Notably, labor availability in the study area is highly favorable, with more than 100 individuals per km² and approximately 2,200 seaweed farmers in South Halmahera Regency. This represents a significant advantage, as labor shortages are often identified as a major constraint in aquaculture development (Engle et al., 2021). The strong human resource base may compensate for infrastructural limitations and support sustainable industry expansion.

The integrated spatial suitability analysis demonstrated that the majority of the study area (403.02 ha) falls within the most suitable category, with only a small portion classified as moderately suitable (55.86 ha). This dominance of most suitable areas highlights the strong potential for seaweed aquaculture development in Bisa Island. These findings are consistent with previous studies conducted in other Indonesian coastal regions, such as South Sulawesi, North Kalimantan, and Lampung, which emphasize the importance of spatial suitability analysis in guiding sustainable aquaculture planning (Yulianto et al., 2017; Maradhy et al., 2022; Sarjito et al., 2022). The results of this study further demonstrate that integrating environmental and infrastructural parameters through spatial multi-criteria evaluation provides a robust framework for identifying optimal aquaculture sites and supporting evidence-based coastal resource management.

CONCLUSION

This study demonstrates that the coastal waters of Bisa Island, South Halmahera Regency, generally exhibit environmental conditions that are suitable for the development of *K. alvarezii* seaweed aquaculture. The physical and chemical characteristics of the waters fall within

acceptable ranges for seaweed growth, indicating a supportive environment for sustained production and ecological stability. The spatial suitability analysis further reveals that the total potential area for seaweed cultivation reaches 458.88 ha, of which the vast majority is classified as most suitable covering 403.02 ha, followed by moderately suitable areas of 55.85 ha. These findings highlight the significant potential of Bisa Island as a priority site for sustainable seaweed aquaculture development. Despite certain infrastructural limitations, particularly in terms of accessibility to harbors and settlements, the overall suitability remains high due to favorable environmental conditions and strong labor availability. Therefore, the integration of environmental and infrastructural parameters through spatial multi-criteria evaluation provides a reliable basis for supporting strategic planning and sustainable coastal resource management in the region.

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