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Environmental Suitability and Supportability for Seaweed Cultivation Development in Terujung Coastal Area, Labuhan Aji, Sumbawa

Hasdinar Firda[1*], Bambang Widigdo[2], Zairion[2,3], Gatot Yulianto[2]

[1] Megister Program of Coastal and Marine Resources Management, Faculty of Fisheries and Marine Science, IPB University, Bogor.
[2] Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, IPB University, Bogor.
[3] Center for Coastal and Marine Resources Studies, IPB University, Bogor.

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Corresponding Author:
Hasdinar Firda
dinarfirda.jou@gmail.com

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Abstract: Global demand for seaweed continues to increase, encouraging Indonesia as a major producer to optimise cultivation areas in a sustainable manner. The Terujung coastal area, located within Saleh Bay, has long been used as a location for seaweed cultivation, but has not been scientifically evaluated in terms of aquatic suitability and carrying capacity. This study aimed to assess the level of suitability and environmental capacity of the area to support the sustainable cultivation of Eucheuma sp. in a sustainable manner. Analyses were conducted using a Geographic Information System (GIS)-based spatial approach and evaluation of water physico-chemical parameters and other supporting factors. Results showed that of the total area of 459,576 hectares, approximately 22.92% was classified as suitable, 58,09% as conditionally suitable, and 18.99% as unsuitable. The calculation of carrying capacity shows that only 89,35 hectares of area can be optimally utilized, with a maximum capacity of 178 longline units. This study provides a scientific basis for aquaculture zoning planning based on environmental suitability in the Terujung Coastal water.

Keywords: Coastal Terujung; Land Suitability; Seaweed; Supportability

Introduction

Seaweed is one of the abundant marine commodities in Indonesian waters (Dahuri et al., 2004; Suparmi & Sahri, 2009) and is a leading export product of the marine and fisheries sector. This commodity is relied upon in revitalisation programmes due to its advantages, such as extensive export opportunities, simple and easy-to-master cultivation technology, and a short cultivation cycle that quickly yields profits (Ahriani. et al., 2022; Nuryanto & Dewi, 2016). Domestic and export demand continues to increase in line with the growth of the seaweed-based industry. According to data from the Ministry of Marine Affairs and Fisheries (2023), Indonesia controlled approximately 12.3% of the global market in 2021 and is one of the main players in the seaweed industry. To strengthen this position, the Ministry designated 15 provinces as national production centres in 2023, with West Nusa Tenggara ranking fourth as a high-productivity region.

West Nusa Tenggara Province, particularly Sumbawa Regency, plays a crucial role in national seaweed development, having served as a pilot region for export-oriented seaweed development from 2010 to 2012 with outstanding performance. One of the core areas designated by the Sumbawa Regency government is Terujung Village, Labuhan Aji Village, Tarano District Suniada & Indriyawan (2014), which is part of Saleh Bay. This area is strategic for the marine sector of West Nusa Tenggara due to its ecological and geographical potential (Yulius. et al., 2016). Although seaweed cultivation activities have been ongoing in this area for a long time, there has been no specific evaluation regarding the suitability of the area and the

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environmental carrying capacity of the coastal waters in Terujung. However, this area is important and is included in the marine conservation area designated in the 2022 West Nusa Tenggara Province Coastal and Small Islands Zoning Plan (RZWP-3-K) document as a limited use zone.

Observations and information from local farmers, along with data from the Empang-Terano Marine and Fisheries Resources Information Centre in 2024, indicate that seaweed farming activities in this area from 2019 to 2023 showed signs of declining production. This decline is suspected to be closely related to the deterioration of water quality, such as high cultivation density, continuous cultivation without land recovery periods, the influx of waste from aquaculture activities, and sediment accumulation due to runoff from corn farming activities in the coastal land area. The combination of these factors can disrupt ecosystem stability and reduce seaweed productivity. This indicates that seaweed cultivation in this area has not considered land suitability and environmental carrying capacity. Mualam (2022) emphasises that cultivation issues often arise due to the lack of scientific principles in site selection and planning. Therefore, this study aims to evaluate the suitability of the waters and carrying capacity of the cultivation area in the Terujung coastal region to prevent environmental damage that could impact seaweed productivity and ensure that the location used can support productive and sustainable cultivation. Additionally, it aims to provide input for cultivators and stakeholders in optimally managing the area.

Method

Time and Place

This study was conducted from May to August 2024. The research location was in the coastal waters of Terujung Hamlet, Labuhan Aji Village, Tarano Subdistrict, Sumbawa Regency, West Nusa Tenggara Province (NTB), with eight water quality observation stations as shown in Figure 1. Stations 1, 2, and 3 represent existing seaweed cultivation areas, station 4 represents areas with high marine transportation activity, stations 5, 6, and 7 represent potential seaweed cultivation areas, and station 8 represents coastal waters near river mouths and close to fisheries cultivation activities. Ex-situ water quality parameter analysis (nitrate and phosphate) was conducted at the Analytical Chemistry Laboratory of the Faculty of Mathematics and Natural Sciences, Mataram University, and the West Nusa Tenggara Testing and Calibration Laboratory.

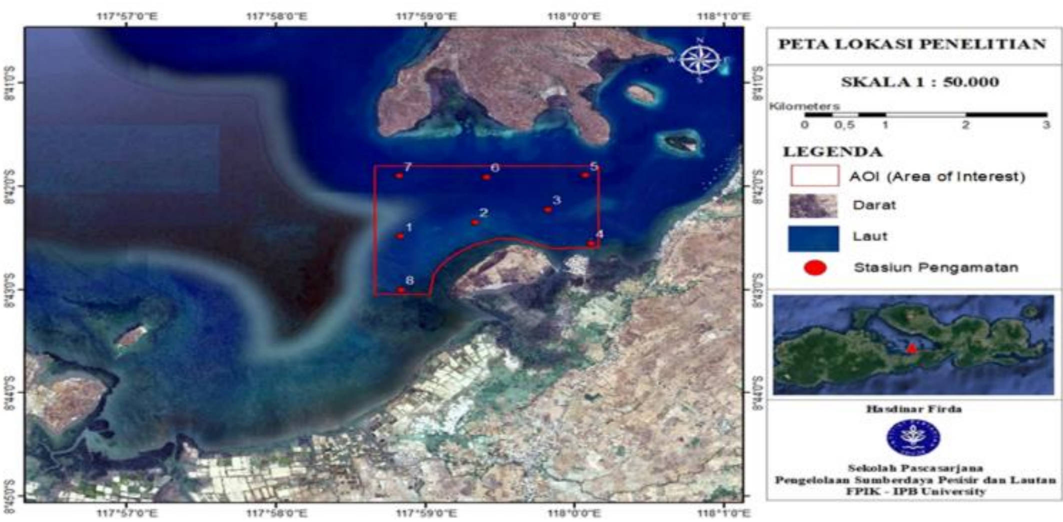

Figure 1. Research location map

Type and Source of Data

The data used includes primary and secondary data. Primary data was obtained through field observations, sampling, and interviews with 30 respondents selected purposively based on their expertise in seaweed cultivation. Secondary data was obtained from previous studies and relevant agencies such as the Empang-Tarano PSDKP Technical Implementation Unit of the Sumbawa Regency Marine and Fisheries Service.

Suitability Analysis

Water suitability analysis is important to ensure that seaweed cultivation sites have environmental conditions that support optimal growth and productivity. The sustainability of cultivation is highly dependent on proper environmental management (Annisa et al., 2023). This study uses a Geographic Information System (GIS) to evaluate water suitability in the coastal area of Terujung.

According to Radiarta et al. (2018), GIS is widely used in the analysis of suitability and carrying capacity of water areas. Eight physical-chemical parameters analysed include temperature, salinity, pH, turbidity, depth, current, phosphate, and nitrate, as well as supporting factors that influence seaweed growth. The processed water quality data were visualised into thematic maps, then overlaid to produce a suitability map based on the Mualam (2022) method, which includes weighting, scoring, and calculation of the suitability index (SI). Weights and scores are derived from a modified suitability matrix based on several references from (Hasnawi et al., 2013; Nashrullah et al., 2021; Sari et al., 2019; Yusuf, 2013) and other references (Table 1). The suitability index analysis was calculated using the following Formula 1.

$$IKK = \sum_{i=1}^{n} (\beta i \times Si) \quad (1)$$

Description:
IKK = Area suitability index
βi = Weight of the i-th water parameter
Si = Score of the i-th water parameter

Table 1. Seaweed Cultivation Suitability Matrix

Parameter	Classification of Scores Based on Suitability Level Si			Weight βi	Weight x Maximum Score	Reference
	Suitable S1 (5)	Suitable Conditional S2 (3)	Not Suitable (1)			
Temprature (°C)	28 – 32	20-<27 dan >32-33	< 20 atau > 33	3	15	(Mualam et al., 2022) (Nashrullah et al., 2021)
Depth (m)	1-<10	11-15	<1 dan 15>	2	10	(Sari et al., 2019) (Yusuf, 2013)
Salinity (ppt)	30 – 33	28-<30	<28 dan >33	3	15	(Yusuf, 2013) (Hasnawi et al., 2013)
Current (m/s)	0.2 – 0.30	0.1–0.19 dan 0.31-0.4	<0.10 dan 0.40>	3	15	(Yusuf, 2013) (Sari et al., 2019)
Brightness (m)	>3	1 – 3	<1	3	15	(Sari et al., 2019) (Mualam et al., 2022)
pH (-)	6.5 – 8.5	4-<6.4 dan 8.6-9	<4 dan >9	2	15	(Nashrullah et al., 2021) (Noor, 2015)
Nitrate (mg/L)	>0.10	0.001 – 0.1	<0.001	2	15	(Zainuddin, 2023) (Sari et al., 2019)
Phosphate (mg/L)	>0.10	0.001 – 0.1	<0.001	2	10	(Zainuddin, 2023)
protection	Safe	Quite Safe	Not Protected	3	5	(Hasnawi et al., 2013) (Yusuf, 2013)
Security	Safe	Quite Safe	Fairly Safe	1	5	(Hasnawi et al., 2013) (Radiarta et al., 2005) (Sirajuddin, 2008)
Location Access	Easy	Quite Easy	Difficult	1	5	(Radiarta et al., 2005)
Total Weight x Score				25	125	(Sirajuddin, 2008)

After determining the suitability index for each observation station, the suitability class category is calculated using the following analysis formula 2.

$$Int = \frac{\Sigma(B_i \times S_i)_{max} - \Sigma(B_i \times S_i)_{min}}{K} \quad (2)$$

Int = Interval of suitability class
∑Bi x Simax = Total weight of the highest score
∑Bi x Simin = Total weight of the lowest scoring
K = Number of classes (3 classes)

Suitability class categories:
Suitable (SS) = X2 - X3
Suitable (S) = X1 -X2
Not suitable (N) = Xo -X1
Xo = The smallest value from the product of weight and score
X1 = The sum of Xo with the class interval (Xo + Int)
X2 = The sum of X1 with the class interval (X1 + Int)
X3 = The largest value of the product of weight and scoring.

Supportability Analysis

The carrying capacity of water is an important factor in maintaining the sustainability of seaweed farming and other food production systems in coastal areas. If the intensity of seaweed cultivation exceeds the carrying capacity of the aquatic environment, the activity will not be sustainable in the long term. As a result, aquaculture will cause ecological pressure, degrade environmental quality, and lead to suboptimal yields. In addition, expected ecological benefits, such as the ability of seaweed to absorb nutrients in water, will not be achieved efficiently (Nuryadin & Soewardi, 2015).

The approach to measure and assess the carrying capacity of waters in seaweed aquaculture refers to methods developed (Mosriula, 2019; Rauf, 2012). This method includes several stages, ranging from collecting data on the aquatic environment, analyzing water quality, evaluating the carrying capacity of the ecosystem, to calculating the optimal amount of cultivation area that is still acceptable without disturbing the environmental balance. Determination of the area of suitability of suitable waters based on the results of analysis using GIS, and then used in the analysis of the carrying capacity of waters, where there are 3 classes of suitability, namely very suitable, suitable, and unsuitable. Calculation of water capacity (KP_{RL}) based on the percentage of utilization, which can be utilized continuously for seaweed cultivation. This calculation is based on the cultivation unit used in the research location.

$$KP_{RL} = \frac{L_2 - L_1}{L_2} \text{ X } 100\% = \frac{(p_2 \text{ x } l_2) - (p_1 \text{ x } l_1)}{(p_2 \text{ x } l_2)} \text{ x } 100\% \quad (3)$$

Description:
KPRL = Water capacity (%)
L_1 = Area of managed aquaculture unit (m^2)
p_1 = Length of managed aquaculture unit (m)
l_1 = Width of the managed aquaculture unit (m)
L_2 = Area of suitable aquaculture unit (m2)
p_2 = Length of suitable cultivation unit (m)
l_2 = Width of suitable cultivation unit (m)

Determination of the carrying capacity of waters for seaweed aquaculture (DD_{LRL}) based on water capacity can be determined based on the area of waters suitable for long line seaweed aquaculture multiplied by the percentage of water capacity, using the following Formula 4.

$$DD_{LRL} = LPS_{RL} \text{ x } KP_{RL} \quad (4)$$

Description:
DD_{LRL} = Water carrying capacity for seaweed cultivation (unit)
LPS_{RL} = Water area suitable for seaweed cultivation (hectares)
KP_{RL} = Water capacity (hectares)

Determining the number of units that can support seaweed activities is done using the following formula.

$$JUB_{RL} = \frac{DD_{RL}}{LUB} \quad (5)$$

Description:
JUB_{RL} = Number of seaweed farming units
DDL_{RL} = Water carrying capacity for seaweed cultivation (hectares)
LUB = Cultivation unit area based on SNI (50 m x 100 m)

Result and Discussion

Water Suitability

The success of seaweed aquaculture is strongly influenced by water conditions, especially water quality from physical, chemical, and biological parameters. Therefore, analysing the suitability of waters is an important step taken before conducting cultivation activities. Soejarwo et al. (2019) explained that understanding the exact condition of the waters can avoid the risk of cultivation failure caused by environmental mismatches, and can optimise the production of seaweed cultivation to run well and sustainably. In assessing the suitability for seaweed cultivation, it is necessary to consider various important aspects such as protection, security of location access, and sea transport activities. Mosriula (2019) explains that determining the suitability of land for seaweed cultivation needs to consider security factors, protection, potential conflicts, ease of accessibility, and ecological conditions of the waters. In addition, sea transport aspects such as shipping lanes are also a major consideration. Hussin et al. (2015) also argues that the suitability of the area is not solely determined by biophysical conditions, but also by social and institutional readiness, including the adoption of longline methods that can be carried out by farmers supported by training and institutions.

Analysis of area suitability based on water quality parameters shows that the Terujung coastal area fulfils the eligibility criteria for seaweed farming activities. The results of spatial mapping conducted using ArcGIS software identified that of the total area of 459.576 hectares, approximately 105.336 hectares were classified in the Suitable (S1) category, 266.966 hectares (30.10%) were in the Suitable Conditional (S2), and 87.274 hectares were in the Not Suitable (N), category (Table 2).

Table 2. Land Area of Water Suitability for Seaweed Cultivation in the Terujung Coast.

Suitability Criteria	Area (Hectares)
Suitable	105,336
Suitable Conditional	266,966
Not Suitable (N)	87,274
Total	459,576

Spatial mapping was carried out by combining several thematic maps (overlays) using ArcGIS 10.8 software to produce a seaweed cultivation suitability map that classifies areas into three categories: Suitable, Conditionally Suitable, and Unsuitable (Figure 2).

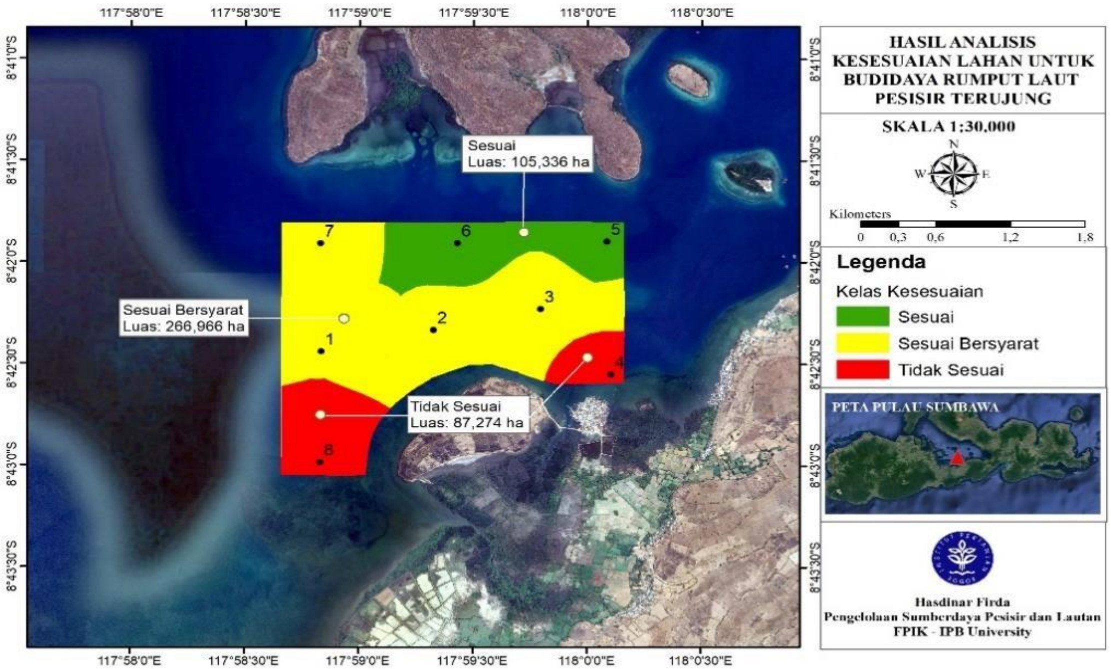

Figure 2. Land Suitability for Seaweed Cultivation in the Terujung Coastal Zone

Data analysis shows that ST1, ST2, ST3 and ST7 are classified as Conditionally Compliant. ST1, ST2 and ST3 are existing areas. Continuous cultivation activities without interruption are suspected to have caused a decline in water quality at these stations. Several water quality parameters such as temperature, depth, and current are not ideal. Although the longline method used is an environmentally friendly aquaculture method, the presence of aquaculture waste such as unused seaweed and damaged aquaculture equipment that accumulates at the bottom of the water can increase organic load and potentially disrupt water quality for aquaculture. ST 7 is located in an area with optimal water quality; however, based on supporting parameter data, the area is exposed to wind and waves. Geographically, ST7 appears to be surrounded by small islands, giving the impression of being sheltered. However, in reality, this location is open to the influence of the open sea because the wide gaps between the islands allow currents and waves from the open sea to enter, making this location less than ideal for seaweed cultivation, which requires calm and sheltered waters. Additionally, ST7 faces higher access costs due to its significant distance from settlements and transportation routes, making it more difficult to access and prone to security risks such as theft or damage to equipment, especially without supervision, thus posing challenges in terms of security and access. ST1, ST2, ST3, and ST7 can be used for seaweed cultivation but require special management to ensure that cultivation activities proceed smoothly, thereby avoiding negative impacts on the environment and production outcomes.

ST5 and ST6 fall into the Suitable category because water quality indicates very optimal conditions. In terms of protection, these locations are not directly exposed to large waves as they are situated in a cluster of small islands in the northern region, shielding them from wave impacts and keeping the waters relatively calm. The safety of the location is maintained because ST5 and ST6 are located near the fishing routes of local fishermen when they go out to sea and return to their settlements, so human activities around the location are more routine and intense. Accessibility is relatively easy, especially via the sea route from Station 4, which is the centre of coastal community activities. Therefore, Stations 5 and 6 are highly recommended as priority locations for the productive and sustainable development of longline seaweed cultivation.

ST4 and ST8 are classified as Unsuitable. ST4 is located on the coast, which serves as a landing site for maritime transport and is very close to residential areas. Water quality at this location is suboptimal, with low transparency, strong currents due to shipping activity, and high phosphate levels reflecting anthropogenic pressure. This location is not sheltered or directly exposed to the sea, lacks natural barriers such as small islands or headlands to dampen waves, and is in an area heavily trafficked by ships, making it prone to damage to cultivation equipment, despite its easy access. Meanwhile, ST8 is also unsuitable for aquaculture due to very low transparency, weak currents, and high phosphate-nitrate concentrations, likely from runoff from nearby ponds and agricultural land, and its location at a river mouth. The location is sufficiently protected and easily accessible, but from a security perspective, it requires special attention as it is located at the administrative border between villages with high social dynamics, which could pose challenges for sustainable aquaculture management.

Carrying Capacity

The carrying capacity of waters for seaweed cultivation in Pesisir Terujung is calculated based on the capacity of cultivation units using the long line method, referring to the maximum number of long line units that can be installed in a water area without causing environmental degradation. Yustika et al. (2022) explain that different seaweed cultivation techniques will result in different environmental carrying capacities because the carrying capacity using a water capacity approach is influenced by the appropriate cultivation area and the cultivation method applied. Byron & Costa-Pierce (2013) also explain that carrying capacity is an important concept that can help determine seaweed cultivation capacity based on ecological limits. The process of analysing the water carrying capacity of the Terujung Coastal Area involves three main stages: determining the Suitable Water Area (LPSRL), calculating the Water Capacity (KPRL), and establishing the Number of Seaweed Cultivation Units (JUBRL).

The analysis results show that the total area that meets the Suitable (S1) and Conditionally Suitable (S2) categories for seaweed cultivation is 372,302 hectares. The water capacity calculation (KPRL) aims to determine how much of the cultivation area can be effectively utilised. The results show that only 24.80% or 89,355 hectares of the total area can be technically optimally used for the horizontal installation of long line units in seaweed cultivation in Pesisir Terujung. The remaining approximately 282,947 hectares are not utilised due to technical, ecological, and inter-unit spacing considerations to prevent environmental degradation and ensure long-term production sustainability, enabling cultivation activities to proceed efficiently and sustainably. Overall, ecological, social, and technical approaches in selecting areas and cultivation methods are key to managing coastal areas for sustainable seaweed cultivation development.

The calculation of the number of seaweed cultivation units (JUBRL) is an estimate of the maximum number of cultivation units that can be installed in a water area without exceeding the environmental carrying capacity. The JUBRL analysis results indicate that the Terujung Coastal Area has a maximum capacity to accommodate up to 178 long line units for seaweed cultivation activities. This number indicates the maximum limit of cultivation space utilisation that is still within the environmental carrying capacity threshold. If the number of cultivation units exceeds this capacity, there is a risk of water quality degradation, which could impact seaweed growth, nutrient absorption efficiency, and the health and productivity of the cultivation ecosystem, thereby disrupting the sustainability of the cultivation business itself. As stated by Yuniarsih et al. (2014), cultivation activities must consider environmental capacity; if conducted excessively beyond the carrying capacity, issues such as declining water quality and disease risks may arise. Therefore, the coastal management strategy for seaweed cultivation development in Terujung must strictly adhere to scientifically calculated carrying capacity limits to ensure the long-term sustainability and efficiency of cultivation. A total of 178 long line units serve as a key indicator in the spatial planning of sustainable seaweed cultivation areas in the Terujung coastal region. The potential of 178 units not only indicates sufficient area but also reflects the ecological capacity of the water to support intensive development that remains environmentally friendly.

The seaweed cultivation area in Terujung has significant potential for sustainable seaweed cultivation development. This potential is not only based on the ecologically suitable area size but also on the environmental capacity to accommodate intensive cultivation activities. Therefore, the planning of seaweed cultivation development in the Terujung Coast must be aligned with environmental carrying capacity and supplemented with a regular monitoring system for environmental parameters. Wijayanto et al. (2022) state that effective management of environmental carrying capacity can maintain the sustainability of cultivation and the economic value of cultivation activities.

Conclusion

The Terujung coast has significant ecological potential for seaweed cultivation. The results of the cultivation area suitability analysis indicate that of the total area covered by the study, 459,576 hectares, 105,336 hectares (22.92%) are classified as Suitable, 266,966 hectares (58.09%) as Conditionally Suitable, and 89,274 hectares (18.99%) as Unsuitable. Based on the carrying capacity analysis, considering technical and geographical aspects in the field, approximately 89.35 hectares can be utilised, with a maximum capacity of 178 long line units for seaweed cultivation activities. The Terujung coastal area is suitable to be designated as a sustainable seaweed cultivation zone, with management based on suitability and carrying capacity to ensure long-term productivity and the sustainability of the coastal ecosystem

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Author Contributions
Hasdinar Firda collected the data, was fully responsible for the implementation of the research and the preparation of the manuscript. Prof. Dr. Ir. Bambang Widigdo, Dr. Zairion, M.Sc., and Dr. Gatot Yulianto, M.Si. provided guidance, input, and direction during the research process and manuscript revision. All authors have read and approved the final version of the manuscript for publication.

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Conflicts of Interest
The author declares that they have no competing interests.

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