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MORPHOMETRIC CHARACTERISTICS AND HABITAT SUITABILITY OF GREEN SEA TURTLE IN SMALL ISLANDS: A CASE STUDY OF MARINE CONSERVATION AREAS IN WEST SUMATRA, INDONESIA

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Abstract: This study aims to identify the morphometric characteristics of the green sea turtle (*Chelonia mydas*) and the biophysical attributes of its nesting and feed habitats on three small islands within marine conservation areas in West Sumatra, namely Kerabak Ketek Island, Bindalang Island, and Kasiak Island. Field observations employed purposive sampling to measure carapace dimensions and nesting habitat parameters while oceanographic data were used to assess feeding areas using GPS mapping and biophysical analyses. Results indicated that green sea turtles at Kerabak Ketek Island exhibited the largest morphometric traits, with an average carapace length of 94.0 cm, compared with 88.6 cm at Kasiak Island, and 78.0 cm at Bindalang Island. Nesting habitat analysis highlighted key ecological factors, namely medium sand, nest vegetation, and beach slope, which support optimal nesting. Feeding areas at Kerabak Ketek Island, characterised by high coral cover (65%) and macroalgae (14.4%), offered superior conditions compared with other islands. Integrated conservation strategies, including habitat monitoring, coral transplantation, and community engagement are recommended to address environmental pressures. Such approaches support the sustainable management of green sea turtle populations, contributing to marine ecosystem balance and aligning with broader conservation goals.

Keywords: Marine conservation area, biophysical characteristic, green sea turtle, nesting habitat, feeding area.

Introduction

Conservation involves deliberate efforts to safeguard the planet's rich biodiversity, ensuring the health and longevity of ecosystems. Marine and fisheries conservation particularly concentrates on preserving aquatic habitats and marine species, highlighting their intricate relationships and ecological dependencies. In Indonesia, sea turtles are recognised as a conservation priority due to their migratory nature. The Indonesian government has identified sea turtles as one of the 11 most critical species requiring immediate protection. Additionally, the inclusion of sea turtles on the International Union for Conservation of Nature's (IUCN) "Red List" underscores their critical status and the urgent need for protective actions (Salleh *et al*., 2022). Of the seven global sea turtle species, four inhabit West Sumatra, Indonesia: The green sea turtle (*Chelonia mydas*), leatherback turtle (*Dermochelys coriacea*), hawksbill turtle (*Eretmochelys imbricata*), and olive ridley turtle (*Lepidochelys olivacea*). The green sea turtle (*Chelonia mydas*), listed as endangered since 2004, holds significant importance in conservation efforts (Seminoff, 2004).

In West Sumatra Province, efforts by local authorities to conserve sea turtles were initiated in 2003 through the establishment of several small islands as designated marine conservation zones. However, these early initiatives lacked

strategic coordination and long-term viability. It was not until the introduction of Government Regulation No. 60/2007 that conservation areas specifically targeting turtles and marine ecosystems began to take shape across different regions (Zamzami *et al*., 2021). Presently, six Marine Conservation Areas (MCAs) in West Sumatra have been identified as priority zones for protecting sea turtles. These areas stretch from Pasaman Barat Regency in the north to Pesisir Selatan Regency in the south, also encompassing the Mentawai Islands located roughly 100 miles off Sumatra's coast. The six conservation zones include: (1) the Bunga Strait MCA in the Mentawai Islands, (2) the MCA in Pesisir Selatan, (3) the MCA in Padang, (4) the MCA in Batang Gasan, (5) the MCA in Padang Pariaman, and (6) the MCA in Pasaman Barat (Halim *et al*., 2001).

On the western coast of Sumatra, small islands where turtles nest are sites of significant exploitation. Traditionally, local communities have harvested turtle eggs for either trade or personal consumption. As Zamzami *et al*. (2021) highlighted, in the Mentawai Islands, turtles are often captured using traditional nets, with the catch typically reserved for cultural and ceremonial purposes. This practice, deeply rooted in local traditions and passed down through generations, continues to persist. Ardiansyah (2010) notes that establishing turtle conservation zones within MCAs in West Sumatra integrates diverse management methods and frameworks.

However, existing national and international conservation standards provide valuable guidelines that can support these efforts. When properly implemented, conservation initiatives on small islands in West Sumatra have the potential to transform these areas into exemplary sites for green sea turtle conservation, serving as replicable models for other regions. Such efforts could make meaningful contributions to Indonesia's broader conservation objectives, promoting sustainable marine resource use, and protecting endangered species within national waters.

Building on this context, the primary aim of this research is to explore the morphometric traits of the green sea turtle and assess the biophysical features of their nesting and feeding habitats across three small islands within the MCAs of West Sumatra, namely Karabak Ketek Island, Bindalang Island, and Kasiak Island. The specific objectives of the research are to (1) investigate variations in green sea turtle morphometric characteristics; (2) analyse the biophysical and ecological conditions of green sea turtle nesting habitats; (3) determine the optimal features of feeding habitats that facilitate green sea turtle growth and development; and (4) propose a comprehensive, sustainable green sea turtle conservation strategy for the MCAs in West Sumatra, aimed at enhancing marine ecosystem sustainability and securing green sea turtle protection.

This research introduces new insights into the effectiveness of conservation efforts, providing recommendations for local governments to improve the coordination and implementation of protective measures, particularly by integrating local communities and stakeholders in conservation decision-making processes.

Methods

Research Location

This research focused on the nesting season of the green sea turtle in Kasiak Island in Pariaman City, Bindalang Island in Padang City, and Karabak Ketek Island in Pesisir Selatan Regency. These islands are located within the MCAs of West Sumatra, which extends approximately from 0.5°S to 1.5°S latitude and from 99.5°E to 100.7°E longitude, covering coastal and marine zones along the Indian Ocean. Sampling locations were selected using purposive sampling within the designated nesting areas on each island in the protected conservation zone, as illustrated in Figure 1.

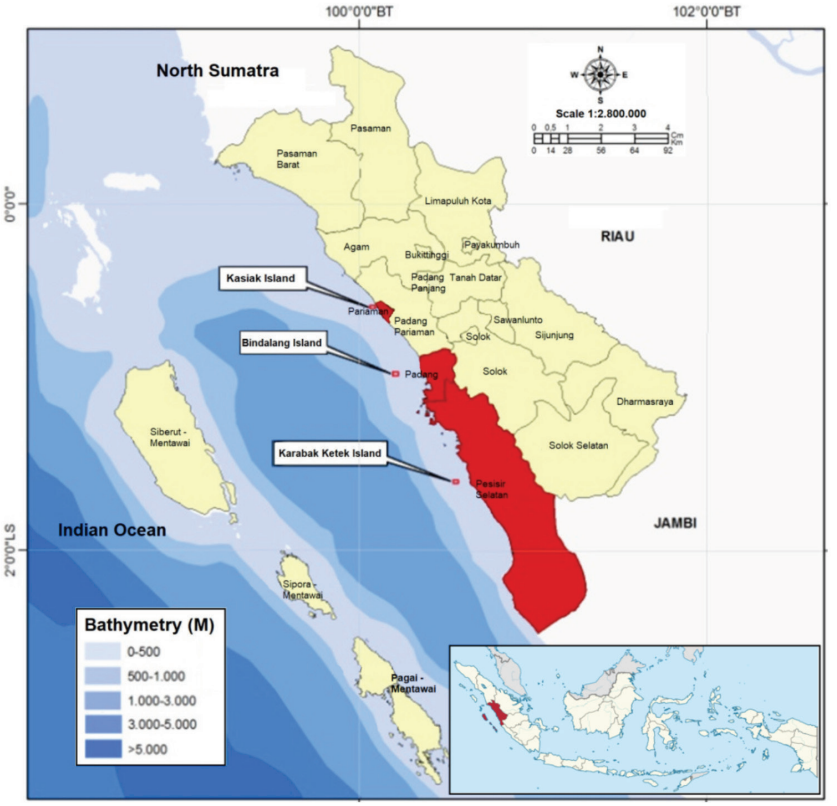

Figure 1: Map of research locations in the Mandeh region

Data Analysis Technique

Sampling Methods for Morphometric Characteristics of Green Sea Turtles

The measurement of adult female green sea turtles focused on assessing carapace dimensions, specifically the Curved Carapace Length (CCL) and Curved Carapace Width (CCW). CCL was measured along the curve of the carapace length while CCW was measured across its width, using a 100 cm plastic tape measure, with measurements recorded in centimetres. Additional morphometric characteristics recorded included carapace length (PK), carapace height (TK), head length (PKa), head width (LKa), head height (TKa), front leg length (PKD), front leg width (LKD), hind leg length (PKB), hind leg width (LKB), and tail length (PE) (Bolten *et al*., 1999). Oceanographic data such as sea-surface temperatures and bathymetry were also collected to understand environmental factors affecting turtle growth and habitat use. Further details are presented in Figure 2.

Sampling Methods for Nesting Habitat Ecology

Field surveys were conducted to observe green sea turtle nesting habitats. The steps for measuring the ecological aspects of the nesting habitats were as follows: (1) beach width (LP), measured parallel to the coastline, from the low tide point to the lowest point of the beach and (2) beach slope (KP), determined by comparing the width of the beach with the distance between the highest tide and lowest ebb (tg = D/H). Additionally, sand samples from turtle nests were collected to assess the physical characteristics of the nesting habitats.

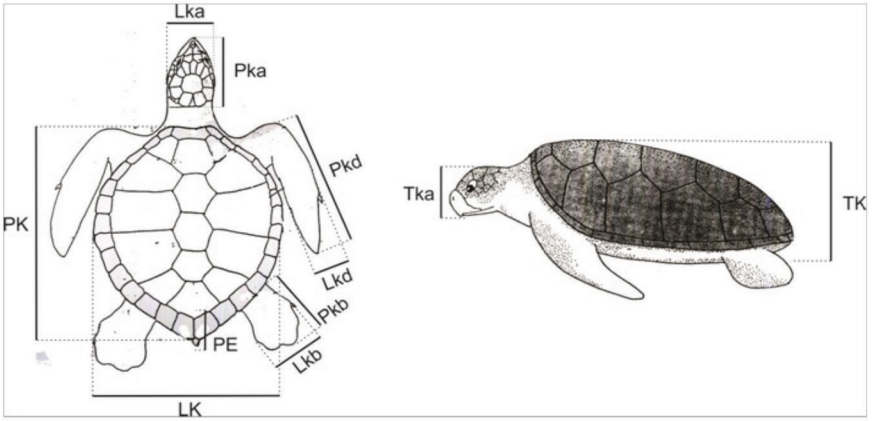

Figure 2: Measurement of morphometric characteristics of green sea turtles

These observations included: (1) nest sand characteristics, where 1 kg of sand was taken from the top layer of the nest and analysed in the laboratory using the sieve method to determine sand grain size fractions; (2) body nest Width (LSTb), measured by the diameter of the upper part of the nest; and (3) egg nest width (LSTr), measured by the diameter of the upper section of the egg chamber. Oceanographic data, including sea-surface temperatures and bathymetry were analysed to explore how water conditions and underwater topography influence nesting site selection.

Sampling Methods for Biophysical Characteristics of Feeding Areas

The biophysical sampling of green sea turtle feeding areas aimed to collect data on habitat conditions that support feeding activities. This method involved observation, mapping, and environmental data collection.

First, observations of biophysical parameters were conducted by identifying locations where turtles surfaced in the late afternoon, just before nesting, to pinpoint feeding areas within the marine habitat. Second, each turtle's emergence location was recorded with Global Positioning System (GPS) coordinates to map feeding zones. Third, area coverage was estimated by tracking turtle movements with binoculars from shore to gauge the size of feeding areas. Fourth, GPS-marked emergence points were mapped to outline the entire feeding area, clearly visualising accessible feeding habitats. Fifth, feed types and composition were assessed by diving at specific coordinates to examine the available food sources. Finally, the 50-m line intercept transect method was employed to assess coral reef conditions and substrate coverage.

Measurements of biophysical water parameters, including water depth (DP), sea-surface temperature (SuP), and water salinity (SalP) were conducted using a deep gauge, Secchi disc, and thermometer while salinity was measured with a salinometer. Oceanographic parameters such as sub-surface temperatures and bathymetry were included to assess their role in supporting feeding areas and identifying suitable habitats.

Data Analysis

This research analysed data using three approaches, namely (1) Principal Components Analysis (PCA) to simplify complex data to identify main environmental factors (temperature, beach conditions, and feed availability) (Kent *et al*., 2022); (2) the Kruskal-Wallis test to compare data from the three locations to identify significant differences in green sea turtle characteristics and habitat conditions, particularly non-normally distributed data; and (3) integrated and sustainable conservation approach that used the analysis

results to propose a sustainable green sea turtle conservation strategy (Gulo *et al*., 2024).

Results

Morphometric Characteristics of Green Sea Turtle

The distribution of morphometric characteristics of green sea turtles was observed across three distinct islands, namely (1) Kasiak, located 3.50 km off the coast of Pariaman City to the north, covering 2.00 ha with 1.00 ha of vegetation and 0.09 ha of built-up land, featuring diverse fine sandy beaches; (2) Bindalang, situated west of Padang City, spanning 17.00 ha with 12.00 ha of vegetation and no permanent structures, 17.00 km from Muara Padang Beach, with white sandy beaches, making it an ideal nesting ground for green sea turtle; and (3) Karabak Ketek in Pesisir Selatan Regency, which spans 3.00 ha with 1.00 ha of vegetation and 0.10 ha of built-up land, located 9.50 km offshore, and also surrounded by white sandy beaches.

Of the 11 morphometric characteristics measured, six were identified as primary features. In Factor F1, the main characteristics are carapace length (PK), carapace height (TK), and front leg length (PKD) while in Factor F2, they are head width (LKa), head height (TKa), and front leg width (LKD).

The average carapace lengths (PK) were 88.6 cm for Kasiak, 78.0 cm for Bindalang, and 94.0 cm for Karabak Ketek. The average carapace heights (TK) were 20.3 cm, 15.9 cm, and 20.3 cm while front leg lengths (PKD) were 41.4 cm, 31.3 cm, and 40.7 cm, respectively. For head width (LK), the measurements were 10.1 cm, 10.7 cm, and 10.4 cm. The head height (TKa) measurements were 9.7 cm, 11.4 cm, and 11.0 cm, front leg width (LKD) values were 14.0 cm, 15.9 cm, and 12.4 cm, respectively. Further details are presented in Table 1.

Table 1 presents the average morphometric measurements of green sea turtles across three islands within the MCAs in West Sumatra. Karabak Ketek shows the largest carapace length (PK) measurements, followed by Kasiak and Bindalang. The carapace height (TK) values are similar for Karabak Ketek and Kasiak while Bindalang has the smallest carapace thickness. The front leg length (PKD) of turtles on Kasiak is greater than that on Karabak Ketek and Bindalang. Other variables such as head width (LKa), head height (TKa), and front leg width (LKD) also vary between the islands, with notable differences in TKa and LKD.

The biplot from the PCA in Figure 3 illustrates the contribution of each variable to the variations in turtle sizes across the islands, with data points representing the size distribution of green sea turtles on each island. Further details are presented in Figure 3 and Table 2.

A PCA was conducted to examine the morphometric characteristics of green sea turtles. According to Page-Karjian *et al*. (2022), PCA is an effective method for analysing complex biological data, as it allows for the identification of key variables that contribute to variations within a population. Previous studies have also demonstrated that PCA is useful for revealing patterns that might not be evident through univariate analyses (Serttaş *et al*., 2018).

Table 1: The average for morphometric characteristics of green sea turtle

Islands	PK (cm)	TK (cm)	PKD (cm)	LKa (cm)	TKa (cm)	LKD (cm)
Kasiak	88.60 ± 5.13^{b}	20.30 ± 0.84^{a}	41.40 ± 3.36^{a}	10.10 ± 0.74	9.70 ± 0.67^{c}	14.00 ± 1.58^{b}
Bindalang	78.00 ± 2.35^{c}	15.90 ± 0.74^{c}	31.30 ± 2.59^{c}	10.70 ± 0.76	11.40 ± 0.42^{a}	15.90 ± 1.43^{a}
Karabak Ketek	94.00 ± 5.41^{a*}	20.30 ± 1.92^{b*}	40.70 ± 1.86^{b*}	10.40 ± 1.08	11.00 ± 0.79^{b*}	12.40 ± 2.07^{c*}

Note: Superscript letters above the mean values in different columns indicate significant differences ($\alpha < 0.05$).

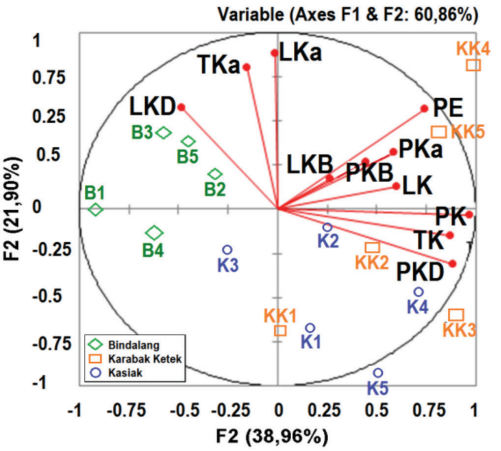

Figure 3: PCA results for morphometric characteristics of green sea turtles

Among the examined characteristics include carapace length (PK), carapace height (TK), head width (LKa), head length (PKa), front leg width (LKD), and front leg length (PKD). These traits were grouped into two primary clusters. The first principal component (F1) accounted for 38.96% of the observed variation, with traits such as PK, TK, and PKD being the most significant contributors. Meanwhile, the second principal component (F2) explained 21.90% of the variation, with characteristics like LKD, TKa, and PKD playing dominant roles.

Kruskal-Wallis analysis revealed significant differences in PK among the three islands, with Karabak Ketek showing the highest average PK compared with the other islands. Table 1 supports this finding, showing that the average PK on Karabak Ketek (94.0 ± 5.41 cm) is greater than on the other islands, suggesting that these size differences may be linked to the unique environmental conditions on each island.

Nesting Habitat Ecology of Green Sea Turtle

To describe the nesting habitat ecology of green sea turtles that lay eggs on the small islands within the MCAs in West Sumatra, observations were made of the nesting habitat ecology of green sea turtles. The observed characteristics consist of LP, KP, PHa, PSe, LSTb, LSTr, KS, SS, pHS, DST, and VS. The characteristic factors on the F1 axis contributed 22.81% of the variation, with a root characteristic value of 2.51, highlighting PSe, PHa, and VS as the main habitat factors. The second axis F2 contributed 20.47% of the variation with a root characteristic value of 2.25, emphasising LSTb, KS, and KP as important biophysical characteristics.

Of the 11 observed variables, six were identified as the primary factors of green sea turtle nesting habitats, namely PSe, PHa, VS, LSTb, KS, and KP. Further details are provided in Table 3.

Based on Table 3, the nesting habitat ecology of green sea turtles on the three islands highlights the importance of various environmental components in supporting the nesting process. Further details are described as follows:

- Medium sand (PSe) is crucial for nest structure and turtle comfort during egg-laying. The PSe sizes on Kasiak, Bindalang, and Karabak Ketek were 69.63 ± 12.92 mm, 84.83 ± 15.87 mm, and 72.86 ± 13.48 mm, respectively, indicating variations that can influence nest stability and temperature. The differences in PSe size can affect moisture retention and temperature regulation inside the nest, which are vital for successful embryo development.

Table 2: Main morphometric characteristics of green sea turtles

No.	Key Features (F1)	Value (%)	Key Features (F2)	Value (%)
1	Carapace Length (PK)	21.93	Head Width (LKa)	32.13
2	Carapace Height (TK)	17.90	Head Height (TKa)	26.72
3	Front Leg Length (PKD)	18.40	Front Leg Width (LKD)	13.77

Table 3: Average values of nesting habitat ecological variables for green sea turtles

Islands	PSe (mm)	PHa (mm)	VS	LSTb (cm)	KS (%)	KP (°)
Kasiak	69.63 ± 12.92[c]	84.65 ± 6.96	67.50 ± 30.10	137.80 ± 4.82	73.20 ± 7.26	5.10 ± 1.43[c]
Bindalang	84.83 ± 15.87[a]	94.65 ± 5.56	47.50 ± 10.46	141.00 ± 6.89	67.00 ± 4.06	5.55 ± 1.53[b]
Karabak Ketek	72.86 ± 13.4[b]	87.15 ± 6.84	47.50 ± 10.46	136.00 ± 8.46	70.00 ± 6.20	9.60 ± 3.97[a]

Note: Superscript letters above the mean values in different columns indicate significant differences ($\alpha < 0.05$).

- Fine sand (PHa) plays a key role in maintaining nest humidity, which is essential for incubation. The PHa composition on Kasiak, Bindalang, and Karabak Ketek is 84.65 ± 6.96 mm, 94.65 ± 5.56 mm, and 87.15 ± 6.84 mm, respectively, aiding in moisture retention for embryo development. PHa helps maintain a stable microclimate around the eggs, which is important for their proper development.
- Nest vegetation (VS) offers protection, especially from sun exposure, creating a cooler, stable environment. VS levels on Kasiak, Bindalang, and Karabak Ketek were 67.50 ± 30.10, 47.50 ± 10.46, and 47.50 ± 10.46, respectively, supporting optimal conditions for egg incubation. Vegetation also provides shade and protects nests from predators, as well as reducing the heat stress on eggs.
- Nest body width (LSTb) refers to the area turtles create for positioning during egg-laying. The LSTb on Kasiak, Bindalang, and Karabak Ketek were 137.80 ± 4.82 cm, 141.00 ± 6.89 cm, and 136.00 ± 8.46 cm, respectively, indicating adequate space and favourable sand conditions for nesting. The width of the body nest influences how well the turtles can position themselves and the stability of the nest during and after egg-laying.
- Nest humidity (KS) is vital for successful incubation. Recorded humidity levels were 73.20 ± 7.26% on Kasiak, 67.00 ± 4.06% on Bindalang, and 70.00 ± 6.20% on Karabak Ketek, influencing embryo development speed and incubation success. Variations in humidity can impact egg development rates and hatchling success, with higher humidity promoting faster embryo growth and better survival rates for hatchlings.
- Beach slope (KP) is important, as turtles prefer gently sloping beaches for nesting. The KP on Kasiak, Bindalang, and Karabak Ketek are 5.10 ± 1.43°, 5.55 ± 1.53°, and 9.60 ± 3.97°, respectively. Gentler slopes provide more stability and protection from erosion and waves. Steeper beaches such as those found on Karabak Ketek may expose nests to greater risks from erosion and wave action, but still provide suitable conditions for nesting when combined with other favourable factors.

The nesting habitat ecology of green sea turtles varies across each location, with unique attributes supporting successful nesting on the small islands within the MCAs in West Sumatra. Variation in nesting habitat ecology is strongly correlated with the first (F1) and second (F2) axes, as shown by the respective habitat characteristics. For further details, see Figure 4 and Table 4.

The nesting habitat ecology of green sea turtles was analysed using PCA, focusing on parameters such as LP, KP, PHa, PSe, LSTb, LSTr, KS, SS, pHS, DST, and VS. Analysis of 15 sub-stations across three islands within the MCAs in West Sumatra revealed two primary features. The first component (F1) accounted for 22.81% of the variations with a factor loading of 2.51, driven primarily by PSe, PHa, and VS.

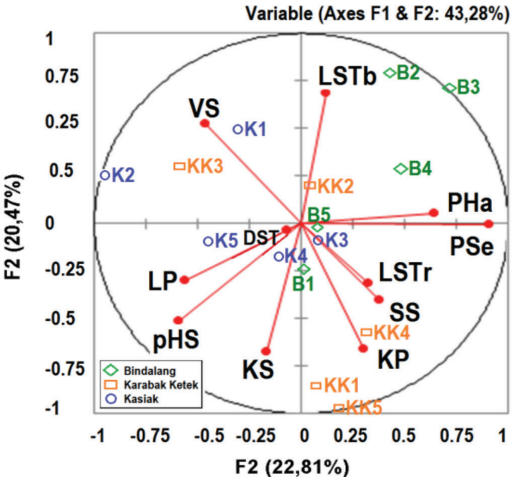

Figure 4: PCA results for the nesting habitat ecology of green sea turtles

The second component (F2) explained 20.47% of the variations with a factor loading of 2.25, influenced by LSTb, KS, and KP. Together, these components highlight the essential characteristics of green sea turtle nesting habitats on these islands. Green sea turtles favour fine sandy beaches, with medium to fine sand particles providing an ideal substrate for nest construction, where PSe, PHa, VS, LSTb, KS, and KP were identified as the main biophysical factors on the three islands. In Table 4, PSe was most prevalent on Bindalang (84.3 ± 5.87 mm), lowest on Karabak Ketek (72.8 ± 6.43 mm), and Kasiak (69.6 ± 12.92 mm), suggesting that finer sand supports nesting suitability. Such biophysical characteristics can help predict nesting populations. During nesting, females typically ascend the beach three to seven times for egg-laying (Witherington & Witherington, 2024), with frequency depending on the biophysical conditions of the nesting area. Of the 11 observed nesting habitat ecology variables, six stood out as primary factors influencing green sea turtle nesting habitats. The PSe fraction was most abundant on Bindalang (B1, B2, B3), but less abundant on Karabak Ketek and Kasiak. KP was critical for green sea turtle approach to nesting locations, with ideal slopes of 30° recorded at Karabak Ketek (K1, K4, K5). Smaller quantities of PSe were noted on Kasiak (K1, K5) and Karabak Ketek (KK3), which are important in maintaining moisture conditions suitable for incubation (Avenant *et al*., 2024).

Kruskal-Wallis analysis showed an average KP value of 6.75 with a standard deviation of 3.19, suggesting an ideal nesting angle. Slope ratings averaged 11.60 on Karabak Ketek, 6.80 on Bindalang, and 5.60 on Kasiak, with a chi-square value of 5.11 and an asymptotic significance level of 0.08. This significance level (5%-10%) indicates notable differences in KP as a measure of nesting habitat for green sea turtle across the three islands.

Biophysical Characteristics of Green Sea Turtle Feeding Areas

To assess the accuracy of land use classification in the Mandeh region, a comprehensive accuracy test was conducted, involving user accuracy, producer accuracy, and overall accuracy. The results for the year 2020 are presented in Table 3. The island clusters along the coast of West Sumatra comprise 186 small islands stretching from north to south along the west coast, all directly bordering the Indian Ocean (Halim *et al*., 2001).

Oveerall, the biophysical characteristics of the feeding areas for green sea turtles nesting on Kasiak, Bindalang, and Karabak Ketek are similar, particularly in terms of biophysical and

Table 4: Main nesting habitat characteristics of green sea turtles

Main Features (F1)	Value (%)	Main Features (F2)	Value (%)
Medium sand (PSe)	32.81	Head width (LKa)	20.78
Fine sand (PHa)	16.43	Head height (TKa)	20.44
Nest vegetation (VS)	12.08	Front leg width (LKD)	19.39

oceanographic features, the presence of coral reef ecosystems that serve as feeding sources. The proximity and similarity in biophysical characteristics among these islands result in several shared features in the feeding areas such as water depth (DP), macroalgae (MA), and temperature (SuP).

Of the six biophysical parameters analysed for the green sea turtle feeding areas, DP showed the strongest positive correlation with the first principal component axis F1, which accounted for 33.43% of the variance and had a root value of 2.01. The second principal component axis F2 explained 26.11% of the variance with a root value of 1.57. The main difference in biophysical characteristics among Karabak Ketek, Kasiak, and Bindalang lies in the DP parameter, where the deepest waters are found at Karabak Ketek and Bindalang while the shallowest depths are observed at Kasiak.

In addition to DP, SuP plays a crucial role in the growth and health of coral reefs, as both minimum and maximum water depths suitable for coral reefs are greatly influenced by SuP. According to Birkeland (1997), coral reefs thrive in SuP ranging from 18°C to 36°C, with an upper tolerance of 36°C to 40°C. The SuP across the three islands within the MCAs in West Sumatra vary, with the highest recorded SuP on Karabak Ketek and Kasiak while lower SuP values are found around Bindalang.

Besides DP, SuP, as a limiting factor plays an essential role in supporting coral reef growth and consequently, the primary food source, namely MA, for green sea turtles, particularly *Sargassum* sp.

Kruskal-Wallis analysis revealed significant differences in DP, SuP, and MA among the three islands, with Karabak Ketek exhibiting the highest average DP and MA compared with the other locations. Table 5 supports this finding, showing that the average DP on Karabak Ketek (12.50 ± 3.50 m) is greater than on Kasiak (8.50 ± 4.18 m) and Bindalang (11.40 ± 4.16 m). Similarly, the MA on Karabak Ketek (14.14 ± 21.18%) is higher than on Kasiak (10.17 ± 16.27%) and Bindalang (2.57 ± 1.29%), suggesting that these differences may be associated with unique biophysical conditions on each island. For further details, refer to Table 5, Figure 5, and Table 6.

PCA of the biophysical characteristics of green sea turtle feeding areas indicates that Karabak Ketek provides optimal conditions, with a high live coral cover of 65%, meeting the criteria for good coral health and making it a favourable feeding and transit area before nesting. In contrast, Kasiak has a lower live coral cover of 18.75% and Bindalang has 23.88% (Table 5).

The SuP around these islands supports coral reef ecosystems, with Karabak Ketek recording the highest average SuP of 30.51°C, compared with 29.70°C on both Bindalang and Kasiak. These temperatures are conducive to coral reef health and beneficial for green sea turtle feeding. A chi-square analysis showed no significant difference in SuP among the three islands, suggesting environmental stability.

However, significant differences were observed in salinity and pH levels, with salinity showing an asymptotic significance of 0.006 and pH of 0.028, both below the 5% threshold, indicating a statistically significant variation. At Karabak Ketek, the combination of higher live coral cover and suitable SuP makes it an ideal habitat for green sea turtles, supporting their feeding and pre-nesting behaviours.

Table 5: The average biophysical characteristics of green sea turtle feeding areas

Islands	DP (m)	SuP (°C)	MA (%)
Kasiak	8.50 ± 4.18	29.70 ± 0.84	10.17 ± 16.27
Bindalang	11.40 ± 4.16	29.70 ± 0.91	2.57 ± 1.29
Karabak Ketek	12.50 ± 3.50	30.51 ± 0.90	14.14 ± 21.18

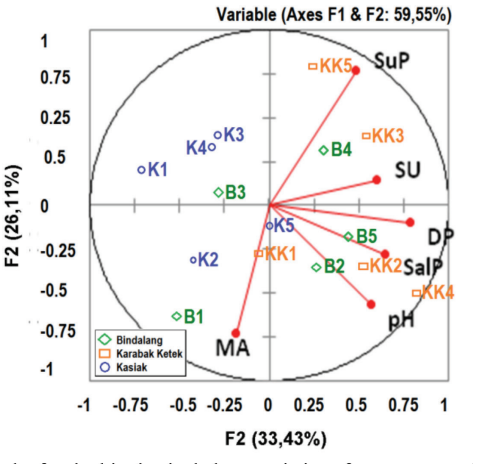

Figure 5: PCA results for the biophysical characteristics of green sea turtle feeding areas

The DP of 12.5 ± 3.50 m further enhances habitat quality by accommodating a diverse range of marine plants, including macroalgage (MA), which contributes 14.44 ± 2.18% to the area's biophysical composition. By comparison, Bindalang's average DP of 11.0 ± 4.16 m is accompanied by lower coral cover and MA presence at 10.17 ± 6.27%, making it less ideal. Kasiak, with a DP of 8.5 ± 4.18 m has the lowest coral cover and MA, further reducing its suitability as a feeding ground.

The availability of live coral cover is a crucial determinant for green sea turtle habitat selection, as turtles rely on coral-associated seagrass and MA for food (Queirós *et al*., 2024). Moreover, variations in salinity and pH levels can affect the distribution of marine flora and fauna, influencing the overall suitability of an area for foraging (Putra *et al*., 2024). The stable SuP conditions in Karabak Ketek support a resilient reef ecosystem, which is essential for sustaining marine biodiversity, including sea turtles.

Integrated and Sustainable Conservation of Green Sea Turtle

Conservation of biodiversity, habitats, and feeding areas within MCAs focuses on subtidal and marine environments, including flora, fauna, and associated historical and cultural values to protect all or parts of these ecosystems (Boudouresque *et al*., 2005; Van den Belt & Cole, 2014; Tantoh, 2022). According to Putra *et al*. (2023), MCAs play a crucial role in sustaining marine biodiversity by providing protected zones where ecosystems can thrive. Salm *et al*. (2000) and Bengen and Dutton (2007) emphasise that MCAs aim to protect both flora and fauna, ensuring these resources benefit future generations. The primary objective of MCA management is to protect ecosystems, populations, and various species at risk of extinction.

Five major challenges confront MCA management (Tony, 2020), namely (1) boundary demarcation of protected areas; (2) habitat degradation along coastlines and marine zones; (3) overfishing within protected zones; (4) low community engagement; and (5) limited conservation awareness among local communities. Dahl (1997) noted that the benefits of conservation include improved ecosystem sustainability, biodiversity preservation, and protection of endemic vulnerable species, with positive economic and scientific impacts. Putra *et al*. (2023) further highlighted that sustainable management of coastal resources should also consider the socioeconomic well-being of coastal communities.

While the use of green sea turtle for economic purposes has long been a part of the coastal culture in West Sumatra, it has the potential to disrupt marine ecosystems. Currently, green sea turtles, once traditionally utilised by local communities are now protected

Table 6: Key biophysical characteristics of green sea turtle feeding areas

Main Features (F1)	Value (%)	Main Features (F2)	Value (%)
Water depth (DP)	30.90	Macroalgae (MA)	34.71
Temperature (SuP)	11.91		

as an endangered species. Dahri *et al*. (2023) noted that coastal development, pollution, and overfishing significantly impacted turtle survival. Research on the morphometric characteristics, nesting habitats, and feeding grounds of green sea turtles on small islands within MCAs in West Sumatra aims to address the challenges in preserving the natural life cycles of these turtle. This research highlights a strong connection among the characteristics of each component on each island, supporting green sea turtle conservation efforts in West Sumatra.

The descriptions for each of the three islands within the MCAs in West Sumatra are outlined as follows:

- Kasiak, Pariaman City (Figure 6) is increasingly facing environmental risks due to the rapid expansion of marine tourism, which has heightened its ecological vulnerability. As shown in the map in Figure 6, developing an effective area management strategy is crucial, with a strong emphasis on conservation efforts for biota, habitat, and food sources. Trihatmoko *et al*. (2024) highlighted that unregulated tourism can severely impact ecosystems essential for the survival of turtles and other marine species. Despite its relatively small size of approximately 2 ha, Kasiak Island boasts 9 ha of coral reef coverage. Geographically, the island is located within the Universal Transverse Mercator (UTM) coordinate system, with its position ranging from approximately 634200 to 634800 meters East and 9933700 to 9934300 meters South. These coordinates

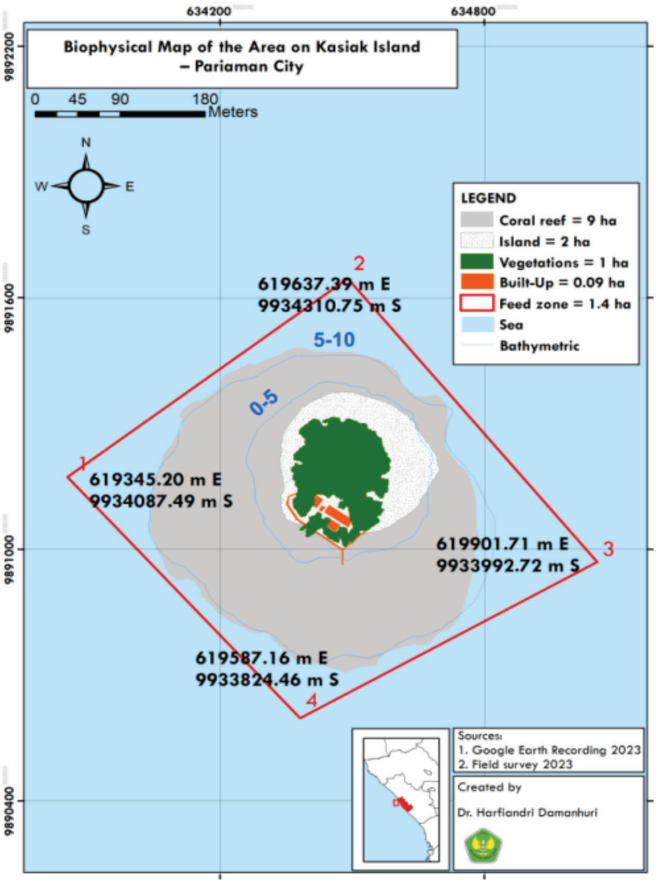

Figure 6: Map of Kasiak Island

delineate the marine conservation area, which requires continuous monitoring and effective management interventions. To ensure sustainable tourism, appropriate management strategies and geospatial data analysis are essential for guiding conservation efforts. As emphasised in the flowchart, ongoing monitoring should be conducted to assess whether tourism activities align with conservation objectives. If adverse impacts are detected, conservation efforts should shift toward habitat and population protection, as outlined in the resource management strategy to mitigate the pressures caused by tourism.

- Bindalang, Padang City (Figure 7), designated as a marine park, provides an ideal habitat for green sea turtles due to its extensive vegetation and coral reefs spanning 72 ha. The map in Figure 7 highlights ecosystem balance, biodiversity protection, and sustainable natural resource management as key priorities. Wyneken *et al*. (2013) argued that small islands serve as crucial shelters for marine life, particularly green sea turtles, by providing stable environments. The sandy beaches surrounding Bindalang further facilitate nesting activities while its well-preserved coastal habitat ensures safe and successful reproduction. Geographically, Bindalang Island is located within the UTM coordinate system, with its position ranging from approximately 633400 to 634800 meters East and 9890000 to 9893800 meters South.

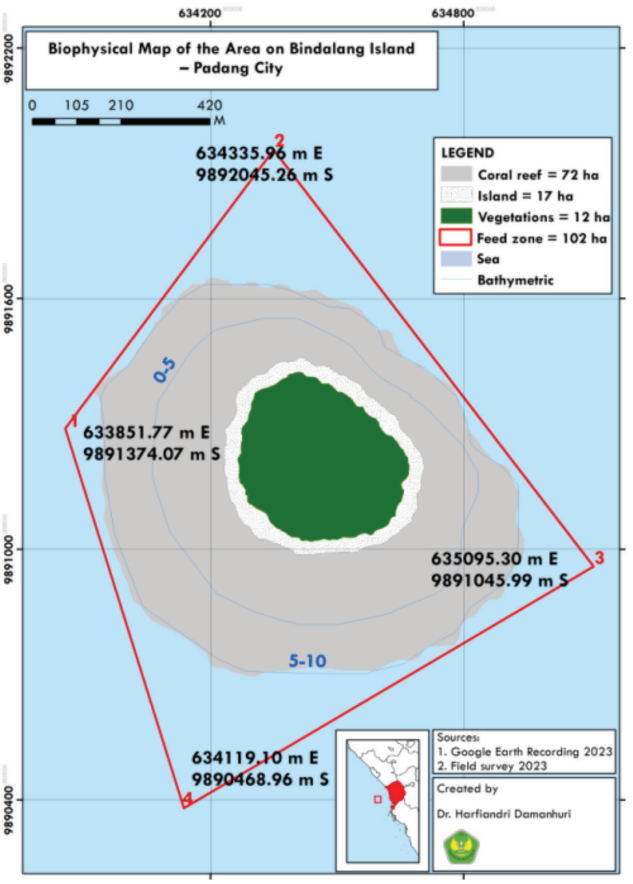

Figure 7: Map of Bindalang Island

These coordinates define the protected MCA, ensuring the long-term sustainability of marine resources. Consistent monitoring underscores the significance of ongoing conservation initiatives, which are essential for maintaining a balanced ecosystem that benefits both marine life and local communities. The integration of geospatial analysis and conservation strategies enhances the effectiveness of management interventions, securing a sustainable future for Bindalang biodiversity.

- Karabak Ketek, Pesisir Selatan (Figure 8), boasts a live coral cover of 65%, making it one of the most suitable habitats for green sea turtles in West Sumatra. This abundance of coral aligns with the bio-ecological factors, which are essential for sustaining healthy marine populations. Saengsupavanich *et al*. (2024) emphasised that well-preserved coral reefs are vital for marine biodiversity, providing food sources and shelter. The island's gently sloping sandy shores offer an ideal nesting environment, supported by stable beach slopes and nearby vegetation. Geographically, Karabak Ketek Island is positioned within the UTM coordinate system, with its location ranging from approximately 672000 to 673400 meters East and 9821800 to 9822900 meters South. These coordinates define the MCA ensuring long-term habitat protection for green sea turtles and associated marine biodiversity. According to the flowchart in Figure 9, the "action, steps, and measures" section is particularly relevant here, as proactive conservation strategies are necessary to preserve the island's rich habitat. Continuous

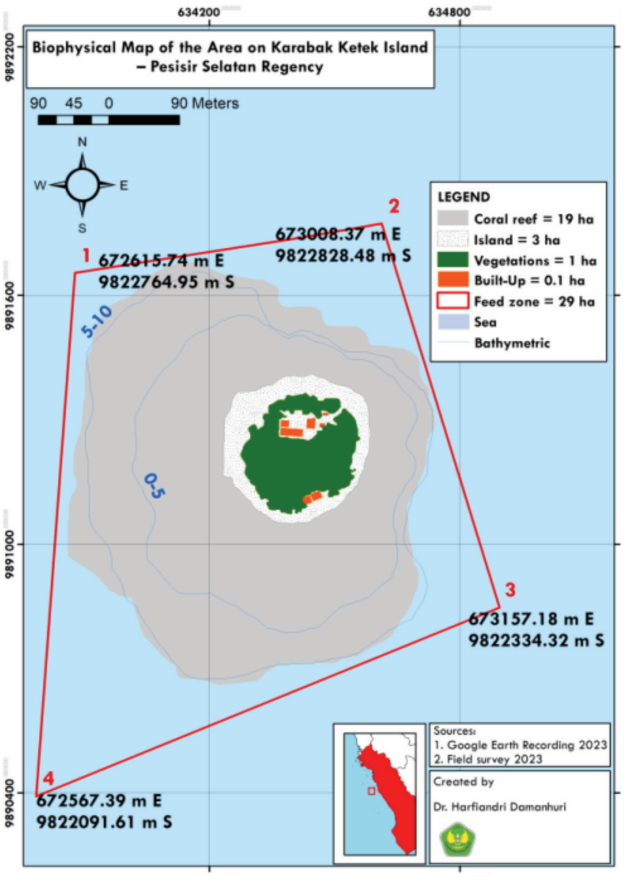

Figure 8: Map of Karabak Ketek Island

monitoring and environmental assessments play a crucial role in ensuring that biotic and ecological conditions remain aligned with conservation objectives. If imbalances are detected, targeted conservation measures can be implemented under priority resource management strategies, reinforcing the island's role as a critical marine sanctuary.

The integrated and comprehensive green sea turtle conservation model, derived from the combination of three main characteristics, namely morphometric characteristics, nesting habitat ecology, and feeding areas is illustrated in Figure 9.

The flowchart in Figure 9 shows that integrated turtle conservation management focuses on key processes, including monitoring, resource management, habitat development, and active conservation measures to ensure the sustainability of green sea turtle habitats.

Discussions

A positive correlation between carapace length (PK) and head width (LK) was observed, aligning with findings by Eravci Yalin *et al*. (2024), which suggest that an increase in PK corresponds to a proportional increase in LK. As detailed in Table 1, the average PK of green sea turtles within the MCAs in West Sumatra varied across islands. The highest average PK was recorded on Karabak Ketek, measuring 94.0 ± 5.41 cm, followed by Kasiak at 88.6 ± 5.13 cm, and Bindalang at 78.0 ± 2.35 cm. These PK values are shorter than those reported for the green sea turtles along the Mexican coast (Spotila, 2004). Larger green sea turtles were predominantly found on Karabak Ketek and Kasiak, with variations in size likely influenced by feed availability rather than genetic factors. This highlights the significant role of food resources in the growth of green sea turtles.

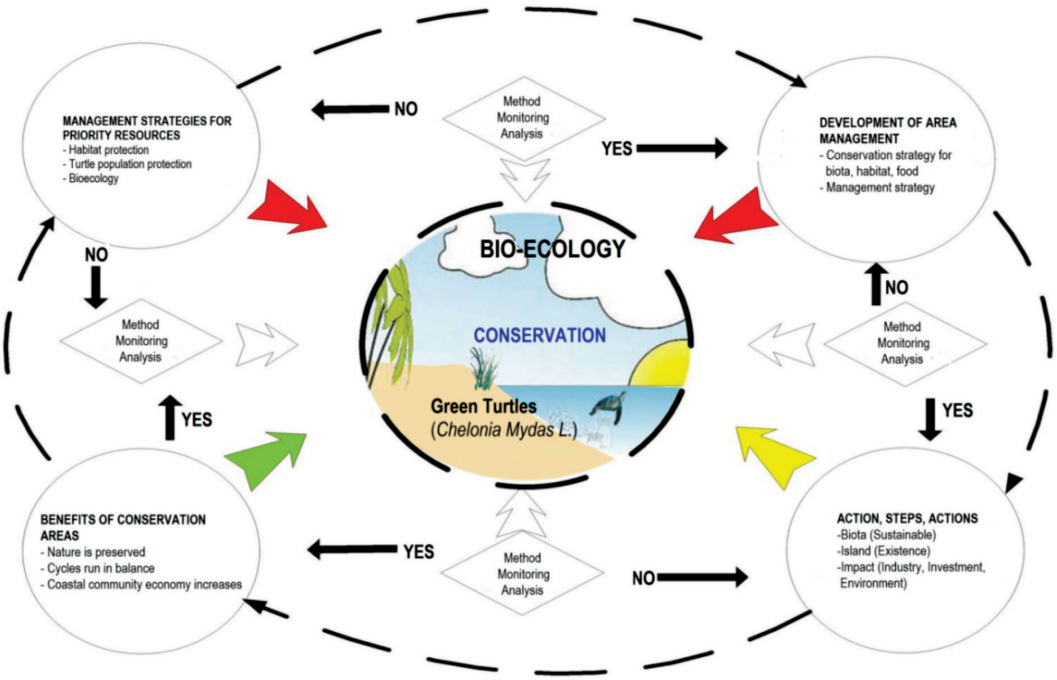

Figure 9: Flowchart of integrated green sea turtle conservation management

Morphometric sizes of green sea turtle in Indonesia were observed to be smaller compared with those in Malaysia (Auliya & Chen, 2024). Notably, larger front leg width (LKD) values were observed in specific individuals from Karabak Ketek (KK3, KK4) and Kasiak (K4). A wider head (LKa) could enhance sensory capabilities, which are crucial for survival in diverse habitats. Additionally, Kasiak (K1) showed larger front leg length (PKD) values while narrower LKa measurements were noted in Karabak Ketek (KK4). High correlation coefficients for morphometric traits, including PK, TK, and PKD, indicate that as these measurements increase, F1 becomes a stronger explanatory factor for size variations among green sea turtles.

The nesting habitat ecology of green sea turtle such as medium sand (PSe), fine sand (Pha), nest vegetation (VS), body nest width (LSTb), nest humidity (KS), and beach slope (KP), serves as an indicator of ideal nesting beaches. These traits correlate positively with larger beach width (LP) and VS. Wider sandy beaches with a higher proportion of medium to fine sand facilitate vegetation growth, supporting nesting activities. Coastal vegetation, especially *Pandanus* sp. is essential for green sea turtle nesting site selection, as it provides crucial cover. A larger LP correlates positively with nesting habitat occupancy. Similar patterns were observed by Witherington and Witherington (2024), who identified coastal vegetation as a determinant for nesting site fidelity due to its role in regulating microclimates.

Furthermore, Immaculate *et al*. (2018) emphasised the importance of medium and fine sand in promoting successful embryonic development. These findings align with Wyneken *et al*. (2013), who highlighted KP and sand composition as main determinants for optimal nesting conditions. The contribution of nesting habitat ecology for green sea turtle is enhanced by the presence of PSe and PHa, which expand the LP area suitable for nesting and increase the role of LSTb. Ideal nesting beaches demonstrate high scores for PSe, PHa, and VS, with Karabak Ketek having a higher component loading (F1) compared with Bindalang and Kasiak, indicating its greater suitability.

Green sea turtles typically inhabit tropical, coral-rich waters, but can adapt to colder marine environments (Poloczanska *et al*., 2009; Mello-Fonseca *et al*., 2021). Coral reefs, often complemented by seagrass ecosystems are fundamental for turtle feeding, mating, and resting before nesting. Immaculate *et al*. (2018) and Prarikeslan *et al*. (2019) identified that four out of nine macroalgae (MA) types, *Enhalus*, *Thalassia*, *Halophila*, and *Cymodocea* are essential feed sources for green sea turtles, underscoring the importance of coral reefs and seagrass ecosystems. Coral reefs are complex assemblages of marine plants, animals, and other biota in a balanced symbiotic environment. Coral growth is most optimal at depths above 25 m, but can extend to 70 m under less ideal conditions (Birkeland, 1997; Suasti *et al*., 2020). Given the role of coral reefs as feeding grounds, protecting these habitats is vital to sustain green sea turtle populations.

These findings suggest that among the three islands, Karabak Ketek stands out as the most suitable habitat for green sea turtle feeding due to its higher coral cover, favourable DP, and stable SuP. Bindalang and Kasiak are comparatively less suitable due to their lower coral and MA cover, though they still provide some level of habitat support. The variations in water salinity (SalP) and pH may also influence habitat quality, emphasising the need for targeted conservation efforts to maintain these critical biophysical conditions.

Research at 15 sub-stations in Kasiak, Bindalang, and Karabak Ketek indicates that Karabak Ketek offers the most suitable habitat, with green sea turtles there showing larger morphometric traits compared with those on the other islands. The sandy beaches of these islands, distinguished by their fine and gently sloping sands are preferred by green sea turtles for nesting. Among the 11 biophysical parameters examined, PHa, PSe, and VS emerged as main factors contributing to nesting success.

To ensure the sustainability of feed sources around Karabak Ketek, a coral transplantation programme is recommended at depths of 5 m to 10 m.

Lal *et al*. (2010) and Dahri *et al*. (2023) emphasise that green sea turtles play an essential ecological role in maintaining the balance of marine ecosystems, especially within the coral reefs and seagrass habitats. By integrating morphometric data, the biophysical aspects of nesting habitats, and feed ecology, a well-rounded, sustainable conservation programme can effectively safeguard green sea turtle populations in West Sumatra while contributing to regional, national, and international conservation objectives.

Conclusions

This research underscores the need for integrated green sea turtle conservation efforts in West Sumatra, focusing on main aspects of morphometric traits, nesting habitat characteristics, and feeding ecology. Among the three islands observed, namely Kasiak, Bindalang, and Karabak Ketek, Karabak Ketek stands out as the most suitable habitat due to its extensive coral cover, favourable sand composition, and sufficient vegetation, supporting both nesting and feeding. Green sea turtles on Karabak Ketek exhibited the largest average body sizes, with critical morphometric traits like carapace length, carapace height, and front leg length showing strong correlations. Nesting habitat analysis identified six essential biophysical factors (medium sand, find sand, nest vegetation, body nest width, nest humidity, and beach slope) that influence nesting success, with Karabak Ketek offering optimal conditions, including stable beach slopes and suitable sand fractions.

In terms of feeding habitat, Karabak Ketek also proved superior, boasting a live coral cover of 65% and abundant macroalgae, critical food sources for turtles. Bindalang and Kasiak showed lower coral cover and feeding suitability, necessitating reef rehabilitation to enhance ecological quality. Integrated conservation efforts such as habitat restoration, coral transplantation, and community involvement are vital for sustaining green sea turtle populations. This approach aligns with global conservation priorities, ensuring the preservation of green sea turtle and their ecosystems in West Sumatra.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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