BIODIVERSITAS
Volume 27, Number 6, June 2026
Pages: 14

ISSN: 1412-033X
E-ISSN: 2085-4722
https://doi.org/10.13057/biodiv/d270606

Water quality and macroalgal community structure across coastal sites in the Bima Sea, Indonesia

NIKMAN AZMIN[1,2,3,♥], CATUR RETNANINGDYAH[1], SUHARJONO[1], WAHYU WIDORETNO[1]
[1]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya. Jl. Veteran, Malang 65145, East Java, Indonesia. Tel./fax.: +62-341-575841, ♥email: biologinikman@student.ub.ac.id
[2]Doctoral Program in Biology, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya. Jl. Veteran, Malang 65145, East Java, Indonesia
[3]Program of Biology Education, Faculty of Teacher Training and Education, Universitas Nggusuwaru. Jl. Pierre Tendean, Bima 84111, West Nusa Tenggara, Indonesia

Manuscript received: 19 April 2026. Revision accepted: 5 June 2026.

Abstract. *Azmin N, Retnaningdyah C, Suharjono, Widoretno W. 2026. Water quality and macroalgal community structure across coastal sites in the Bima Sea, Indonesia. Biodiversitas 27 (6): d270606. https://doi.org/10.13057/biodiv/d270606.* Macroalgae are important primary producers in coastal ecosystems and are highly sensitive to changes in environmental conditions. This study aimed to evaluate the physicochemical water quality and macroalgal community structure in aquaculture and non-aquaculture areas at Wane, Rontu, and Tanjung Mas Beaches, Bima Regency, West Nusa Tenggara, Indonesia. Community structure was assessed using community indices, the Importance Value Index (IVI), and multivariate analyses. A total of ten macroalgal taxa were identified, with *Sargassum* sp. exhibiting the highest IVI values across all study sites (59-81), followed by *Halimeda micronesica*, *Ulva lactuca*, and *Turbinaria* sp., which showed intermediate IVI values. Water temperature and pH remained within ranges suitable for supporting marine life, whereas nitrate and orthophosphate concentrations consistently exceeded water quality reference thresholds across all study sites, although no significant differences were detected among locations ($p>0.05$). The Shannon-Wiener diversity index (H′) ranged from 1.57 to 2.67, with the highest value recorded at the non-aquaculture site in Wane and the lowest at the non-aquaculture site in Tanjung Mas. Multivariate analyses indicated that variation in macroalgal community structure was generally more strongly associated with differences among beaches than with aquaculture and non-aquaculture site categories, although this pattern was most consistently observed at Tanjung Mas Beach. The findings demonstrate that site-specific environmental characteristics play a key role in shaping macroalgal community structure in the Bima Sea. These results highlight the importance of continuous water quality monitoring and location-based coastal management strategies to support macroalgal conservation and the sustainability of tropical coastal ecosystems.

Keywords: Bima Sea, coastal water quality, macroalgal diversity, nutrient enrichment, *Sargassum*

INTRODUCTION

Macroalgal communities are key components of coastal ecosystems, contributing to primary productivity, nutrient cycling, carbon sequestration, and the provision of habitat and food resources for a wide range of marine organisms (Duarte et al. 2022; Hanley et al. 2024). Macroalgae also possess substantial economic and biotechnological value as sources of food, bioactive compounds, pharmaceutical and cosmetic raw materials, and commercially important coastal resources (Krause-Jensen and Duarte 2016; Pessarrodona et al. 2022). Furthermore, macroalgal communities contribute to climate change mitigation through their capacity to absorb and store carbon in both biomass and coastal sediments (Aprilia et al. 2023, Cotas et al. 2023).

Despite their ecological importance, macroalgal communities are increasingly subjected to environmental pressures across coastal regions worldwide. Numerous studies have reported habitat degradation and decline in macroalgal distribution resulting from intensified anthropogenic impacts, including land-derived nutrient inputs, domestic wastewater discharge, aquaculture activities, coastal development, and land-use change (García-Poza et al. 2022; Cannon et al. 2023). These environmental pressures can alter macroalgal community structure, drive shifts in species dominance patterns, and increase the prevalence of opportunistic taxa that are tolerant of environmental disturbance (Andini et al. 2023; Benhniya et al. 2024).

West Nusa Tenggara Province is one of Indonesia's coastal regions with considerable macroalgal biodiversity potential, owing to its highly heterogeneous coastal environments, including variations in substrate type, hydrodynamic conditions, and water quality characteristics (Zulpikar and Handayani 2021; Ghazali et al. 2024). Nevertheless, information regarding the relationship between physicochemical water quality and macroalgal community structure in NTB coastal ecosystems, particularly in Bima Regency, remains limited. Most previous studies have focused primarily on species inventories, distribution patterns, or community descriptions without integrating environmental gradients and macroalgal community responses. Consequently, current understanding of the links between water quality and macroalgal community structure in tropical coastal ecosystems, especially within Bima Regency, remains insufficient (Pelasula et al. 2023; Sjafrie et al. 2024; Rahmadi et al. 2025).

The coastal areas of Bima Regency, particularly Wane, Rontu Beach, and Tanjung Mas Beach, exhibit distinct environmental characteristics in terms of substrate composition, hydrodynamic conditions, and levels of human activity (Rasyid et al. 2025). Wane and Rontu are characterized by more intensive aquaculture and coastal resource utilization activities, which may be associated with variations in nutrient inputs and habitat conditions, whereas Tanjung Mas is subject to relatively lower levels of coastal anthropogenic pressure (Sukarni et al. 2025). These contrasting environmental settings provide an opportunity to compare aquaculture and non-aquaculture sites and to evaluate how variations in water quality are associated with differences in macroalgal community structure across locations at a local scale. Such an approach is essential for improving our understanding of macroalgal community responses to varying environmental conditions in tropical coastal ecosystems.

This study represents one of the first investigations in Bima Regency to integrate physicochemical water quality assessments with analyses of macroalgal community structure across aquaculture and non-aquaculture sites. In addition to evaluating species composition, community indices, and the Importance Value Index (IVI), the study employed Principal Component Analysis (PCA) and cluster analysis to identify patterns of variation in macroalgal communities along environmental gradients. This integrative approach provides a more comprehensive understanding of spatial variation in macroalgal community structure across coastal areas of Bima, a region for which ecological data remain relatively limited.

This study aimed to evaluate the physicochemical water quality and macroalgal community structure at Wane, Rontu, and Tanjung Mas Beaches in Bima Regency, West Nusa Tenggara, Indonesia. Specifically, the study examined whether water quality characteristics and macroalgal community structure differed between aquaculture and non-aquaculture sites and evaluated patterns of community variation among locations in relation to the observed environmental conditions. We hypothesized that spatial variation in environmental characteristics among locations would be accompanied by corresponding differences in macroalgal community structure, as reflected in taxonomic composition, species dominance, and community indices.

MATERIALS AND METHODS

Study area

This study was conducted in the coastal waters of the Bima Sea at three beaches in Bima Regency, West Nusa Tenggara, Indonesia: Wane Beach, Rontu Beach, and Tanjung Mas Beach. Field sampling was carried out from December 2024 to March 2025 (Figure 1). Each beach comprised two observation sites, namely an aquaculture site (C) and a non-aquaculture site (Non-C), which were selected based on substrate type, sediment characteristics, the presence of supporting ecosystems, and the degree of influence from aquaculture activities and surrounding anthropogenic disturbances (Table 1). The straight-line distance between aquaculture and non-aquaculture sites at each beach ranged from 1.85 to 2.20 km and was relatively consistent across all study locations. The primary comparison in this study was conducted between aquaculture and non-aquaculture sites within the same beach (within-site comparison), whereas differences in environmental characteristics among beaches (Wane, Rontu, and Tanjung Mas) were evaluated as an additional source of variation influencing macroalgal community structure.

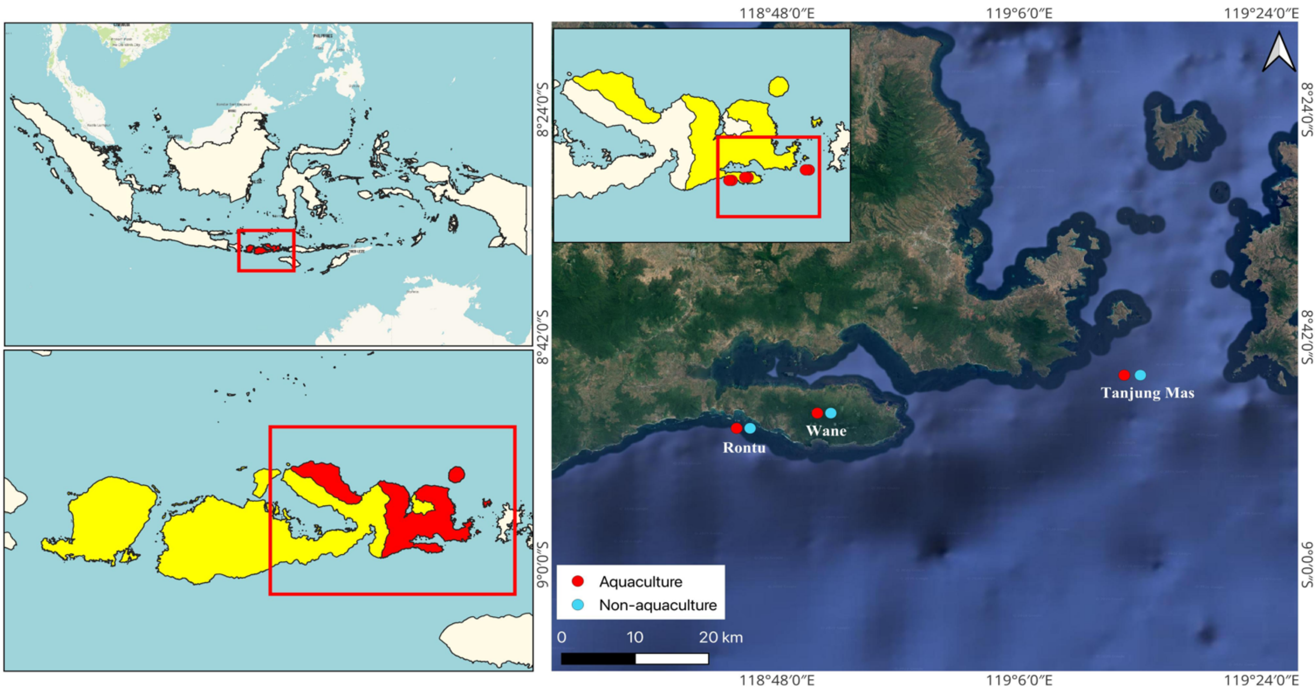

Figure 1. Study area and sampling stations in the coastal waters of Bima Regency, West Nusa Tenggara, Indonesia

Table 1. Description of the study stations in Bima Regency, West Nusa Tenggara, Indonesia, including coordinates in the WGS84 geographic coordinate system

Location	Activity	Coordinates	Description
Wane	Aquaculture	8°49′12″S, 118°45′00″E	Located in Wane Village, Monta District, Bima Regency, on the southern coast of Sumbawa Island. The area is characterized by fishing settlements, active grouper aquaculture operations, and relatively high levels of human activity, as it is also utilized as a coastal tourism destination.
	Non-aquaculture	8°49′12″S, 118°46′00″E	Located in the eastern part of Wane Beach. No active aquaculture facilities were observed at the sampling site during the study period. The area was subject to relatively lower anthropogenic pressure than the adjacent aquaculture site.
Rontu	Aquaculture	8°48′00″S, 118°51′00″E	Located in the southern part of Tangga Baru Village, Monta District, Bima Regency. This site is characterized by active marine aquaculture facilities, including grouper and lobster farming operations. The sampling area was situated within a coastal utilization zone used for aquaculture activities and local fisheries.
	Non-aquaculture	8°48′00″S, 118°52′00″E	Located in the eastern part of Tangga Baru Village, separated from the active aquaculture area. No aquaculture activities were observed during the survey period, and the area was primarily used for small-scale fishing activities. This site served as a reference area for comparison with the aquaculture zone.
Tanjung Mas	Aquaculture	8°45′00″S, 119°13′48″E	Located along the eastern coast of Bima Regency. This site supports small-scale marine aquaculture activities and is characterized by relatively sheltered coastal waters.
	Non-aquaculture	8°45′00″S, 119°15′00″E	Located farther from residential areas and aquaculture facilities. No active aquaculture infrastructure was observed during the survey period, and the site was characterized by relatively low levels of anthropogenic pressure.

Aquaculture sites (C) were defined as areas with active marine aquaculture operations, characterized by the presence of aquaculture infrastructure such as floating net cages or other cultivation facilities that were directly observable within the vicinity of the sampling locations. In addition, these sites were situated in areas that were routinely used for aquaculture activities and exhibited relatively high levels of coastal human activity, as determined through field observations and information obtained from local communities. In contrast, non-aquaculture sites (Non-C) were defined as areas lacking active aquaculture facilities, where no aquaculture infrastructure was observed in the vicinity of the sampling locations, and which were located relatively farther from the centers of aquaculture activities than the corresponding aquaculture sites.

Sampling design

The sampling design encompassed three beaches, each divided into aquaculture and non-aquaculture areas, resulting in six site-level sampling units. At each site, three transects were established parallel to the shoreline, with an inter-transect distance of approximately 75 m to adequately capture habitat variability. Quadrat sampling was conducted systematically along each transect. A total of eight quadrats (1×1 m²) were placed along each transect at intervals of approximately 25 m, yielding a total of 144 quadrats across the six study sites (6 sites × 3 transects × 8 quadrats). All transects were established within a relatively uniform shallow subtidal depth range (0.5-3.0 m) at each study site to ensure consistency in sampling conditions and to minimize the influence of depth variation on macroalgal community structure among locations. Sampling was conducted during daylight hours under relatively similar tidal conditions across all sites to reduce the effects of temporal variation on macroalgal distribution and environmental parameters. Transects were positioned within habitats representative of the dominant substrate conditions at each site, consisting of varying combinations of sand, coral rubble, rock, and dead coral, reflecting the local coastal characteristics.

Macroalgal composition and abundance data were recorded at the quadrat level as field observational units. For univariate statistical analyses of water quality parameters, mean values calculated for each transect were used as independent replicates (n: 3 per site) in one-way analysis of variance (ANOVA) and subsequent post-hoc tests. Macroalgal community indices, including the Shannon-Wiener diversity index (H′), Pielou’s evenness index (E), Simpson’s dominance index (D), Margalef’s richness index (d), and the Importance Value Index (IVI), were calculated using data aggregated from all quadrats within each site, resulting in a single community index value for each location. These site-level aggregated values were subsequently used as analytical units in Principal Component Analysis (PCA) and cluster analysis.

For multivariate analyses, including Principal Component Analysis (PCA) and cluster analysis, quadrat- and transect-level data were aggregated at the site level to avoid pseudo-replication and to ensure that the analytical units represented independent site-level conditions. Consequently, both PCA and cluster analysis were based on six site-level observations (three beaches × two management categories). Given the limited number of observations, these analyses were used primarily as exploratory approaches to visualize patterns of association between macroalgal community structure and environmental variables and were not intended to provide robust statistical inference regarding ecological relationships among variables.

Macroalgal sampling

Macroalgal sampling was conducted at three coastal locations in the Bima Sea, namely Wane Beach, Rontu Beach, and Tanjung Mas Beach, each of which was subdivided into aquaculture and non-aquaculture areas. This design resulted in six site-level sampling units representing different environmental and management conditions. At each site, three transects were established perpendicular to the shoreline, and observations were conducted using eight quadrats systematically positioned along each transect to record macroalgal composition, abundance, and community structure. Quadrat-level observations served as field measurements, whereas site-level mean values were used as the primary analytical units in multivariate analyses.

Macroalgal species recorded within each quadrat were identified based on morphological characteristics using standard taxonomic references, and the abundance of each taxon was documented for subsequent ecological analyses. Taxa that could not be reliably identified to the species level were conservatively designated using the qualifiers "sp." or "cf." to avoid taxonomic overinterpretation. As part of the identification process, all observed specimens were photographed in the field and during laboratory examination, serving as photographic vouchers to support taxonomic verification. In addition to conventional identification references, all taxon names were verified and standardized according to the current nomenclature provided by AlgaeBase and the World Register of Marine Species (WoRMS) to ensure taxonomic validity and consistency. During the nomenclatural verification process, all taxon names were re-examined to minimize spelling errors and the use of outdated synonyms, such that only valid and verified taxonomic names were included in the analyses. The primary identification references used in this study included Global Seagrass Research Methods (Short and Coles 2001), Marine Plants of Indonesia (Atmadja and Van Reine 2014), Illustrated Key to the Marine Macroalgae of the Indo-West Pacific (Silva et al. 1996), Seaweeds of the World (Guiry 2010), and Macroalgae of the Tropical Indo-Pacific Region (Trono 1997; Stiger-Pouvreau and Zubia 2020).

To avoid pseudo-replication, quadrat-level observations were averaged at each site prior to conducting Principal Component Analysis (PCA) and cluster analysis, ensuring that the multivariate analyses represented independent site-level conditions rather than repeated quadrat observations within the same marine habitat (Andrew and Mapstone 1987; Salvanes and Jensen 2018). Because the multivariate dataset was reduced to six site-level observations, PCA and cluster analysis were employed as exploratory approaches to visualize patterns of association between macroalgal community structure and environmental gradients. Accordingly, the results of these analyses were interpreted as indicators of ecological patterns and similarities among locations rather than as a basis for robust statistical inference regarding causal relationships among variables. This approach enabled comparisons of macroalgal community patterns among beaches and management categories while maintaining consistency in statistical interpretation.

Water quality measurements

The physicochemical parameters analyzed in this study included water temperature (°C), air temperature (°C), conductivity (S m^{-1}), dissolved oxygen (DO; mg L^{-1}), salinity (PSU), pH, nitrate (mg L^{-1}), and orthophosphate (mg L^{-1}). Measurements of water temperature, salinity, dissolved oxygen, conductivity, and pH were conducted in situ at each sampling site using previously calibrated portable instruments. At each site, measurements were taken along each of the three established transects, yielding three spatial replicates that were treated as independent replicates in the statistical analyses of water quality parameters. Measurements of pH, salinity, dissolved oxygen, conductivity, and water temperature were performed independently on each transect. Consequently, each parameter was represented by three independent spatial observations (n: 3) per site, which were used to calculate the mean±standard deviation (SD) values reported in Table 2. Air temperature was recorded simultaneously during field surveys and was used solely as a supporting environmental descriptor rather than as a direct ecological driver in the interpretation of submerged macroalgal communities. Salinity values were reported in Practical Salinity Units (PSU) and were cross-checked against the original instrument outputs to ensure unit consistency and data accuracy prior to analysis.

Water samples for nitrate and orthophosphate analyses were collected using sterile polyethylene bottles and analyzed ex-situ at the Laboratory of Tropical Ecology and Ecosystem Restoration, Universitas Brawijaya, East Java, Indonesia, following standard methods outlined by APHA (APHA 2017). Water samples were collected from each transect at every study site, resulting in three independent spatial replicates per site for nutrient analyses. The nitrate and orthophosphate concentrations obtained from the three transects were used to calculate the mean±standard deviation (SD) values presented in Table 2. Prior to analysis, samples were filtered through 0.45 µm membrane filters to minimize the influence of suspended particles. Nitrate and orthophosphate concentrations were determined spectrophotometrically using a UV-Vis spectrophotometer. Nitrate was analyzed according to APHA Method 4500-NO_3^- (cadmium reduction method) and measured at a wavelength of 543 nm, whereas orthophosphate was determined using APHA Method 4500-P E (ascorbic acid method) with absorbance measured at 880 nm. Calibration curves were generated using a series of standard solutions, yielding coefficients of determination (R^2) greater than 0.995 to ensure analytical accuracy. The method detection limits were approximately 0.01 mg L^{-1} for nitrate and 0.005 mg L^{-1} for orthophosphate. Instrument calibration and analytical quality-control procedures were performed prior to field measurements and laboratory analyses to ensure the accuracy, precision, and consistency of data across sampling locations.

Statistical analysis

Water quality parameters were analyzed using one-way analysis of variance (ANOVA), followed by post-hoc tests to evaluate differences among locations and management categories at a significance level of $p<0.05$. Data normality was assessed using the Shapiro-Wilk test, whereas homogeneity of variances was evaluated using Levene's test at a significance level of $p<0.05$. The selection of the post hoc procedure, either Tukey's Honestly Significant Difference (HSD) test or the Games-Howell test, was based on whether the assumption of homogeneity of variances was satisfied.

The analytical units used in this study were defined according to the objectives of each statistical analysis. Macroalgal composition and abundance data were collected at the quadrat level as field observational units. Community indices, including the Shannon-Wiener diversity index (H′), Pielou's evenness index (E), Simpson's dominance index (D), Margalef's richness index (d), and the Importance Value Index (IVI), were calculated at the site level using data aggregated from all quadrats within each sampling location. For water quality parameters, mean values derived from three independent transects at each site were used as independent replicates (n: 3 per site) in one-way analysis of variance (ANOVA) and subsequent post hoc tests. Accordingly, transects served as the statistical replicates for analyses of water quality parameters.

To avoid pseudo-replication, macroalgal and water quality data were averaged at the site level prior to conducting Principal Component Analysis (PCA) and cluster analysis. Consequently, the analytical units for both PCA and cluster analysis were the sampling sites (n: 6; three beaches × two management categories). Accordingly, the results of these analyses were interpreted as exploratory patterns rather than as a basis for robust statistical inference. Data aggregated at the site level were therefore used as the analytical units in both PCA and cluster analysis.

Macroalgal community structure was assessed using several ecological indices, including the Shannon-Wiener diversity index (H′), Margalef's richness index (d), Pielou's evenness index (E), Simpson's diversity index, the dominance index (D), and the Importance Value Index (IVI). The Shannon-Wiener diversity index (H′) was calculated to characterize species diversity based on the relative abundance of each taxon, whereas Margalef's richness index (d) was used to evaluate species richness based on the number of taxa and the total number of individuals recorded. Pielou's evenness index (E) was used to describe the distribution of individuals among species within the community, while Simpson's diversity index was applied to assess community diversity rather than the Simpson dominance formulation. The dominance index (D) was used to identify the degree of dominance exerted by particular species within the macroalgal community. The Importance Value Index (IVI) was calculated as the sum of relative density (RD) and relative frequency (RF). Relative cover and biomass were not included in the calculation because this study employed a quadrat-based approach to document species occurrence and abundance, whereas quantitative estimates of macroalgal cover and biomass were not obtained across all sampling locations. Accordingly, the IVI used in this study represents a measure of relative ecological importance based on species distribution and abundance, thereby enabling consistent comparisons among study sites.

Ecological indices were calculated following standard methods widely used in community ecology studies (Shannon and Weaver 1949; Wilhm and Dorris 1968). Water quality analyses were conducted in accordance with standard APHA procedures, whereas Principal Component Analysis (PCA) and cluster analysis were performed using multivariate statistical approaches commonly applied in aquatic ecological studies.

Principal Component Analysis (PCA) ordination was constructed using six site-level observations and eleven physicochemical and macroalgal community variables. Prior to analysis, all variables were standardized using z-score transformation to eliminate the effects of differences in measurement units and value ranges among variables. Because the PCA was based on only six site-level observations, the ordination results were interpreted as an exploratory approach intended to visualize ordination patterns and relative similarities among locations. Site-level mean values were used for both PCA and cluster analysis, whereas quadrat-level observations were retained for the calculation of univariate ecological indices and descriptive statistics.

Importance Value Index (IVI) (Barnes and Mann 2009)

$$IVI = RF + RD$$

Where, IVI is the Importance Value Index, RF is the relative frequency, and RD is the relative density. In this study, the IVI represents only the combined contribution of relative frequency and relative density and therefore does not include relative abundance, relative cover, or other dominance-related components as additional parameters.

Shannon-Wiener diversity index (H') (Shannon and Weaver 1949)

$$H' = -\sum_{i=1}^{S} pi \ln pi$$

Where, H′: Shannon-Wiener diversity index; p_i: proportion of individuals belonging to species i; S: total number of species.

Simpson dominance index (D)

$$D = \sum_{i=1}^{S} pi^2$$

where, D: Simpson dominance Index, p_i: proportion of individuals belonging to the ith species (n_i/N), S: total number of species.

Simpson diversity index (1 − D)

$$1 - D = 1 - \sum_{i=1}^{S} pi^2$$

Where, 1-D: Simpson diversity index, calculated as one minus the Simpson dominance index, p_i: proportion of individuals belonging to the i-th species (n_i/N), S: total number of species.

Margalef's richness index (d)

$$d = \frac{S - 1}{\ln N}$$

Where, S: total number of species recorded in the community, N: total number of individuals.

Pielou's evenness index (E)

$$E = \frac{H'}{\ln S}$$

Where, *E*: Pielou's evenness index, *H'*: Shannon-Wiener diversity index, *S*: total number of species recorded in the community.

RESULTS AND DISCUSSION

Variation in physicochemical water parameters among locations in the Bima Sea

Environmental parameters exhibited variation among the study locations (Table 2). The results of the one-way analysis of variance (ANOVA) and subsequent post hoc tests indicated that several parameters differed significantly among locations ($p<0.05$), as reflected by the different letter notations presented in Table 2. In contrast, nitrate, orthophosphate, dissolved oxygen, water temperature, and air temperature shared the same letter notation across locations, indicating no significant differences between aquaculture and non-aquaculture areas for these parameters. The most pronounced differences among locations were observed for conductivity, which displayed distinct letter notations across nearly all sites, followed by pH and salinity, both of which also exhibited significant variation among beaches.

Nitrate concentrations ranged from 0.11±0.01 mg L^{-1} at the aquaculture site in Wane to 0.31±0.04 mg L^{-1} at the aquaculture site in Rontu, whereas orthophosphate concentrations ranged from 0.11±0.03 mg L^{-1} at the non-aquaculture site in Wane to 0.19±0.10 mg L^{-1} at the non-aquaculture site in Tanjung Mas. Nitrate concentrations at all study sites exceeded both the Indonesian and ASEAN marine water quality standards of 0.06 mg L^{-1}, with exceedance levels ranging from 83% to 417% (Gemilang et al. 2019). This condition is likely associated with a combination of land-based nutrient inputs, including runoff from residential areas and agricultural activities, as well as internal nitrogen cycling processes within coastal ecosystems through organic matter decomposition and sediment nitrification (Boumaiza et al. 2023).

Orthophosphate concentrations likewise exceeded the applicable water quality standards at all locations. Relative to the Indonesian marine water quality standard (0.05 mg L^{-1}), exceedance levels ranged from 120% to 280%, whereas exceedance relative to the more stringent ASEAN standard (0.015 mg L^{-1}) reached 633-1167%. Despite these elevated nutrient concentrations, neither nitrate nor orthophosphate differed significantly among locations or between site categories. This finding suggests that nutrient enrichment across the study area is likely driven by broader regional-scale factors rather than by local differences between aquaculture and non-aquaculture sites.

Table 2. Physicochemical water-quality parameters at aquaculture and non-aquaculture sites in Wane, Rontu, and Tanjung Mas Beaches

Parameter	Activity	Wane	Rontu	Tanjung Mas	Indonesian standard†	ASEAN standard‡
Chemical parameters						
pH	Aquaculture	7.55±0.03^{ab}	8.04±0.02^{a}	8.10±0.01^{b}	7-8.5	-
	Non-aquaculture	7.58±0.03^{ab}	8.04±0.03^{a}	8.12±0.03^{b}		
Salinity (PSU)	Aquaculture	29.81±0.01^{a}	30.16±0.10^{a}	33.66±0.12^{b}	33-34	-
	Non-aquaculture	30.05±0.01^{ab}	33.16±0.10^{b}	35.00±0.13^{c}		
Dissolved oxygen (DO; mg L^{-1})	Aquaculture	4.81±0.03^{a}	4.81±0.03^{a}	4.93±0.01^{a}		
	Non-aquaculture	4.84±0.03^{a}	4.84±0.03^{a}	4.93±0.01^{a}	>5	>4
Nitrate (mg L^{-1})	Aquaculture	0.11±0.01^{a}	0.31±0.04^{a}	0.23±0.01^{a}		
	Non-aquaculture	0.15±0.02^{a}	0.25±0.04^{a}	0.22±0.03^{a}	0.06	0.06
Orthophosphate (mg L^{-1})	Aquaculture	0.17±0.03^{a}	0.15±0.09^{a}	0.18±0.05^{a}		
	Non-aquaculture	0.11±0.03^{a}	0.19±0.10^{a}	0.17±0.07^{a}	0.05	0.015
Physical parameters						
Water temperature (°C)	Aquaculture	29.70±0.01^{a}	30.12±0.03^{a}	29.88±0.01^{a}		
	Non-aquaculture	29.85±0.01^{a}	30.13±0.03^{a}	29.82±0.01^{a}	28-30	25-32
Air temperature (°C)	Aquaculture	28.00±0.01^{a}	28.00±0.01^{a}	26.00±0.01^{a}		
	Non-aquaculture	28.00±0.01^{a}	28.00±0.01^{a}	26.00±0.01^{a}	28-30	-
Conductivity (S m^{-1})	Aquaculture	4.74±0.01^{a}	5.00±0.03^{c}	5.03±0.05^{c}	-	-
	Non-aquaculture	4.88±0.01^{b}	5.01±0.08^{c}	5.03±0.05^{c}		

Note: Values are presented as mean±SD (n: 3). Different superscript letters within the same parameter indicate significant differences among sampling locations based on post hoc tests ($p<0.05$), whereas values sharing the same letter are not significantly different statistically ($p>0.05$), even when numerical differences are present. PSU: Practical Salinity Unit; DO: Dissolved Oxygen. † Indonesian standard refers to Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning Environmental Protection and Management. ‡ ASEAN standard refers to ASEAN Marine Water Quality Criteria (AMWQC)

According to Government Regulation No. 22 of 2021, the recommended pH range for marine biota is 7.0-8.5, with a minimum dissolved oxygen (DO) concentration of 5 mg L^{-1}. The pH values recorded across all study sites fell within this acceptable range, varying from 7.55±0.03 at the aquaculture site in Wane to 8.12±0.03 at the non-aquaculture site in Tanjung Mas. Dissolved oxygen concentrations ranged from 4.81±0.03 to 4.93±0.01 mg L^{-1} and did not differ significantly among locations. Although these values were slightly below the Indonesian marine water quality standard, they remained above the minimum threshold specified by the ASEAN standard (>4 mg L^{-1}). These findings indicate that dissolved oxygen concentrations were close to the applicable water quality reference thresholds; therefore, further ecological interpretation requires additional observations and cannot be based solely on the DO parameter (Fulton et al. 2020; Hamzah et al. 2020). Water temperature (29.70-30.13°C) and air temperature (26.00-28.00°C) were also within the ranges specified by Indonesian water quality standards (28-30°C for water temperature) and did not differ significantly among locations or between aquaculture and non-aquaculture areas.

The observed variation in physicochemical parameters reflects differences in environmental characteristics among the three beaches, with pH, salinity, and conductivity emerging as the parameters that most clearly distinguished the study locations. The highest pH value was recorded at the non-aquaculture site in Tanjung Mas (8.12±0.03), whereas the lowest was observed at the aquaculture site in Wane (7.55±0.03). Salinity ranged from 29.81±0.01 PSU at the aquaculture site in Wane to 35.00±0.13 PSU at the non-aquaculture site in Tanjung Mas. These values were generally close to the Indonesian marine water quality standard (33-34 PSU), although salinity in Wane consistently remained below the reference range, whereas values in Tanjung Mas exceeded it. Conductivity exhibited a similar pattern, with the highest values recorded in Tanjung Mas (5.03±0.05 S m^{-1}) and the lowest at the aquaculture site in Wane (4.74±0.01 S m^{-1}); no regulatory reference standard is currently available for this parameter. The observed variation in pH, salinity, and conductivity likely reflects differences in dissolved ionic content and seawater mass characteristics among study locations. These differences may be influenced by variation in freshwater-seawater mixing, local circulation patterns, and proximity to freshwater sources at each beach (Halabowski and Lewin 2020; Handayani et al. 2023).

Taxonomic composition and importance value index of macroalgae

A total of ten macroalgal taxa were recorded across the six sampling sites in the Bima Sea (Table 3, Figure 2), namely *Chaetomorpha* sp., *Kappaphycus alvarezii*, *Gelidium spinosum*, *Gracilaria* sp., *Halimeda micronesica*, *Padina* sp., *Sargassum* sp., *Sargassum fluitans*, *Turbinaria* sp., and *Ulva lactuca*. Based on their taxonomic composition, the macroalgal community comprised three taxa belonging to Chlorophyta (*Chaetomorpha* sp., *H. micronesica*, and *U. lactuca*), four taxa belonging to Phaeophyceae (*Sargassum* sp., *S. fluitans*, *Turbinaria* sp., and *Padina* sp.), and three taxa belonging to Rhodophyta (*Gracilaria* sp., *K. alvarezii*, and *G. spinosum*).

Figure 2. Representative macroalgal taxa identified from Wane, Rontu, and Tanjung Mas Beaches. A. *Chaetomorpha* sp., B. *Kappaphycus* sp., C. *Gracilaria* sp., D. *Gelidium* sp., E. *Halimeda* sp., F. *Padina* sp., G. *Sargassum* sp., H. *Sargassum* sp., I. *Turbinaria* sp., J. *Ulva lactuca*

Table 3. Presence-absence matrix showing the occurrence of macroalgal taxa at aquaculture and non-aquaculture sites in Wane, Rontu, and Tanjung Mas Beaches

Division	Macroalgal taxa	Wane		Rontu		Tanjung Mas	
		C	Non-C	C	Non-C	C	Non-C
Chlorophyta	*Chaetomorpha* sp.	+	+	+	+	+	+
	Halimeda micronesica	+	+	+	+	+	+
	Ulva lactuca	+	+	+	+	+	+
Phaeophyceae	*Sargassum* sp.	+	+	+	+	+	+
	Sargassum fluitans	+	+	+	+	-	-
	Turbinaria sp.	+	+	+	+	+	+
	Padina sp.	+	+	+	+	+	+
Rhodophyta	*Kappaphycus alvarezii*	+	+	+	+	+	+
	Gelidium spinosum	+	+	+	+	+	+
	Gracilaria sp.	+	+	+	+	+	+

Note: C: Aquaculture, Non-C: Non-aquaculture, (+): the presence of a species, (-): the absence of a species

The presence-absence matrix (Table 3) showed that nine of the ten recorded taxa occurred in both aquaculture and non-aquaculture areas across the three beaches, indicating a relatively broad distribution that was not strongly associated with site category. The only taxon exhibiting a restricted distribution was *S. fluitans*, which was consistently recorded at Wane and Rontu in both aquaculture and non-aquaculture areas but was entirely absent from Tanjung Mas, regardless of site category. This pattern suggests that the occurrence of *S. fluitans* is more strongly influenced by site-specific environmental characteristics than by aquaculture status.

Based on the Importance Value Index (Table 4, Figure 3), macroalgal community structure exhibited distinct dominance patterns among beaches. *Sargassum* sp. consistently recorded the highest IVI values across all study sites, ranging from 59-63 in Wane, 60-72 in Rontu, and 71-81 in Tanjung Mas. The highest value was observed at the non-aquaculture site in Tanjung Mas (IVI: 81), whereas the lowest was recorded at the non-aquaculture site in Wane (IVI: 59). The heatmap presented in Figure 3 further highlights the consistent dominance of *Sargassum* sp., particularly in Tanjung Mas. Notably, *S. fluitans* was completely absent from the aquaculture site in Tanjung Mas (IVI: 0), in contrast to Wane and Rontu, where this taxon exhibited IVI values ranging from 14 to 24. This pattern further supports the presence-absence analysis, suggesting that the distribution of *S. fluitans* is more strongly associated with differences among beaches than with aquaculture status.

In addition to the dominance of *Sargassum* sp., the heatmap in Figure 3 revealed a broader shift in community composition at Tanjung Mas compared with Wane and Rontu. Several taxa consistently exhibited higher IVI values in Tanjung Mas, including *H. micronesica* (23-26, compared with 8-18 in Wane and Rontu), *Turbinaria* sp. (21 in both site categories, compared with 13-15 at the other locations), and *U. lactuca* (20-22, compared with 14-16 elsewhere). In contrast, several taxa displayed lower IVI values in Tanjung Mas, including *Chaetomorpha* sp. (7-9, compared with 12-15 at the other locations), *Gracilaria* sp. (7-13, with the lowest value recorded at the aquaculture site in Tanjung Mas), and *K. alvarezii* (9-16, showing overlapping values but generally lower than those observed in Wane). These patterns indicate that the macroalgal community at Tanjung Mas was not only characterized by a stronger dominance of *Sargassum* sp., but also by a broader shift in overall taxonomic composition relative to the other two beaches. The simultaneous increase in the relative ecological importance of *H. micronesica*, *Turbinaria* sp., and *U. lactuca*, together with the decline of several other taxa, suggests that environmental conditions at Tanjung Mas may favor a distinct assemblage structure compared with Wane and Rontu.

Other taxa, including *U. lactuca*, *K. alvarezii*, *Turbinaria* sp., *Padina* sp., and *Gracilaria* sp., exhibited intermediate IVI values ranging from 6 to 22, whereas *Chaetomorpha* sp., *G. spinosum*, and *S. fluitans* generally showed lower IVI values (0-15). *H. micronesica* displayed a broader range of IVI values (8-26), with the highest value recorded at the aquaculture site in Tanjung Mas (26), indicating that this taxon cannot be considered a consistently low-contributing component of the community. Taxa with intermediate IVI values made important contributions to community structure, whereas taxa with lower IVI values nevertheless played a role in maintaining taxonomic richness and overall community diversity (Innocenti et al. 2018; Martin et al. 2021). The IVI results indicate that *Sargassum* sp. was the only taxon that consistently exhibited dominance across all study locations, whereas *U. lactuca* and *Turbinaria* sp. functioned as subdominant taxa that also contributed substantially to community structure.

The consistent dominance of *Sargassum* sp. across all study locations, particularly in Tanjung Mas (71-81), is consistent with the findings of Basyuni et al. (2024), who identified *Sargassum* as one of the principal components of macroalgal communities in tropical coastal habitats of Indonesia. A similar pattern was observed for *Turbinaria* sp., which exhibited higher IVI values in Tanjung Mas (21) than in Wane and Rontu (13-15). These findings are in agreement with Duarte et al. (2020), who reported that *Turbinaria* species are capable of thriving across a wide range of coastal habitats owing to their high degree of morphological plasticity.

Overall, the IVI patterns indicate spatial variation in macroalgal community structure among beaches. Tanjung

Mas was characterized by a stronger dominance of *Sargassum* sp., accompanied by the absence of *S. fluitans* and shifts in the relative importance of several other taxa, as described above. In contrast, Wane and Rontu exhibited a more even distribution of IVI values among taxa, including the presence of *S. fluitans* at both locations. The stronger dominance of *Sargassum* sp. in Tanjung Mas was also consistent with the lower evenness and higher dominance values recorded at this site (Table 5). These patterns are consistent with the diversity indices and multivariate analyses, both of which indicate spatial variation in macroalgal community composition among study locations. The dominance of *Sargassum* sp. and *Turbinaria* sp. at several sites is also in agreement with previous studies describing these genera as characteristic components of macroalgal communities in tropical coastal ecosystems (Solihuddin et al. 2021; de Melo Soares et al. 2023).

Table 4. Importance Value Index values of macroalgal taxa at aquaculture and non-aquaculture sites in Wane, Rontu, and Tanjung Mas Beaches

Division	Macroalgal taxa	Wane		Rontu		Tanjung Mas	
		C	Non-C	C	Non-C	C	Non-C
Chlorophyta	*Chaetomorpha* sp.	12	14	15	14	9	7
	Halimeda micronesica	8	14	18	15	26	23
	Ulva lactuca	16	14	14	15	22	20
Phaeophyceae	*Sargassum* sp.	63	59	72	60	71	81
	Sargassum fluitans	23	14	16	22	0	0
	Turbinaria sp.	14	13	15	15	21	21
	Padina sp.	13	16	15	15	14	11
Rhodophyta	*Kappaphycus alvarezii*	13	12	11	6	16	9
	Gelidium spinosum	9	13	4	10	9	8
	Gracilaria sp.	13	15	13	13	7	13

Note: C: Aquaculture, Non-C: Non-aquaculture

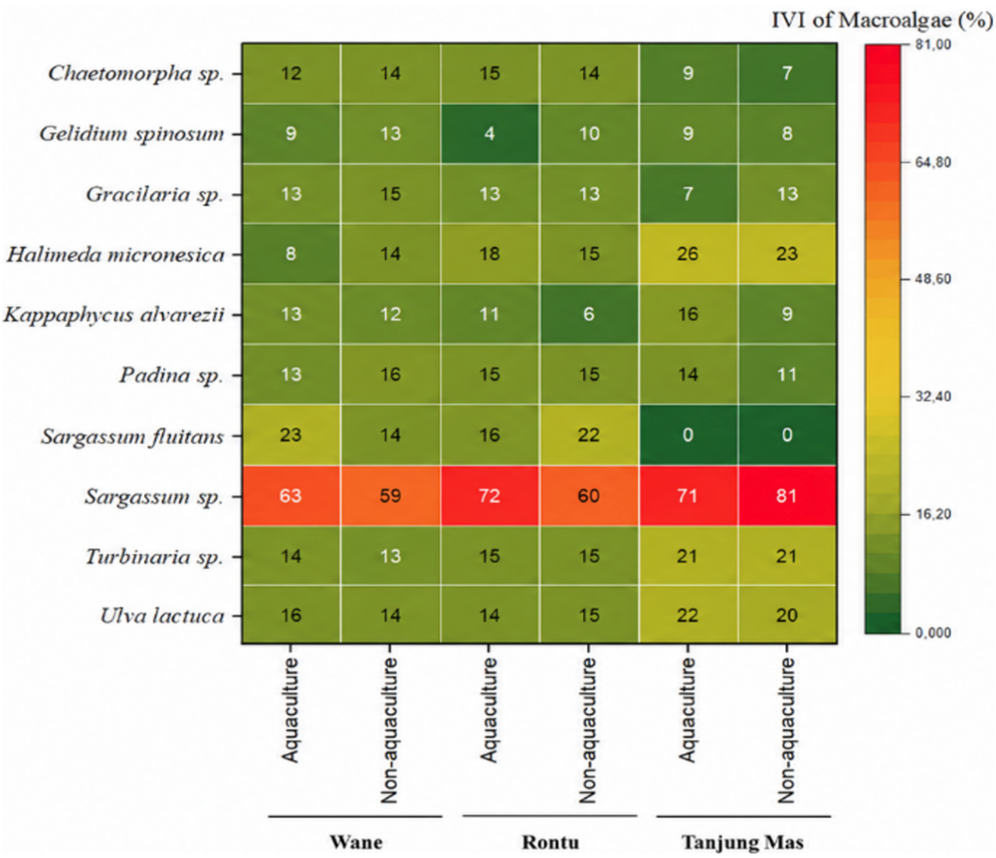

Figure 3. Spatial variation of Importance Value Index of macroalgal taxa at aquaculture and non-aquaculture sites in Wane, Rontu, and Tanjung Mas Beaches

Cluster analysis of macroalgal communities

The grouping of sampling locations in the dendrogram reflects the degree of similarity in community composition, with locations joined at lower linkage distances exhibiting greater similarity than those clustered at higher linkage distances (de Vries et al. 2020; Hadiyanto et al. 2023). Hierarchical cluster analysis based on Euclidean distance and Ward's linkage method (Figure 4) revealed patterns of similarity in macroalgal community composition among the six sampling locations.

At the lowest linkage distances, two initial cluster pairs were formed: Rontu aquaculture and Rontu non-aquaculture (linkage distance: 2.3), and Tanjung Mas aquaculture and Tanjung Mas non-aquaculture (linkage distance: 3.5). This pattern indicates that macroalgal community composition was relatively similar between aquaculture and non-aquaculture areas within each of these beaches. Subsequently, Wane non-aquaculture joined the Rontu cluster aquaculture and non-aquaculture at a linkage distance of approximately 4.7, forming a larger cluster comprising Wane non-aquaculture, Rontu aquaculture, and Rontu non-aquaculture.

The resulting cluster subsequently merged with Wane aquaculture at a linkage distance of approximately 10.7, forming a larger cluster comprising four sampling sites: Wane aquaculture, Wane non-aquaculture, Rontu aquaculture, and Rontu non-aquaculture. In contrast, the Tanjung Mas cluster (aquaculture and non-aquaculture) remained separated from this group until the highest linkage distance (approximately 18), representing the root of the dendrogram. This pattern indicates that macroalgal communities in Tanjung Mas exhibited the lowest degree of similarity to those in Wane and Rontu, whereas communities from Wane and Rontu, regardless of site category, were relatively more similar to one another.

Overall, the dendrogram revealed variation in the degree of similarity among macroalgal communities across the study locations. The clustering pattern suggests that community similarity was more strongly associated with geographic proximity among beaches, particularly between Wane and Rontu, than with aquaculture status. This interpretation is supported by the observation that aquaculture and non-aquaculture sites from both beaches were grouped within the same larger cluster rather than forming separate clusters according to management category. Given that the analysis was based on six site-level observations, the cluster results should be interpreted as an exploratory visualization of relative similarity patterns among locations.

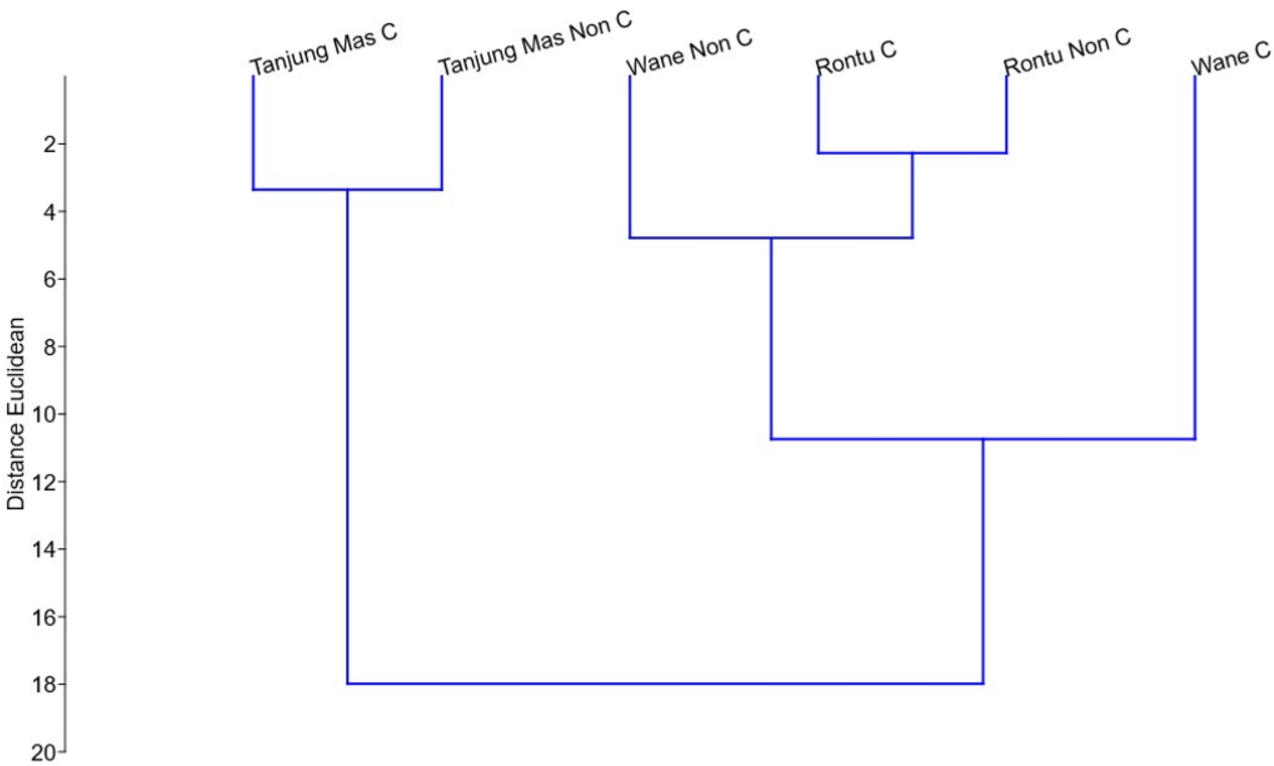

Figure 4. Hierarchical cluster dendrogram of macroalgal community composition across six sampling sites in the Bima Sea, West Nusa Tenggara, Indonesia, constructed using Euclidean distance and Ward's linkage method. Lower linkage distances indicate greater similarity in community composition among sites. The dendrogram illustrates relative patterns of similarity among sampling locations and is presented as an exploratory visualization because the analysis was based on six site-level observations

Macroalgal community structure indices across locations

Macroalgal community indices revealed variation in community structure among beaches, as reflected by total density, taxa richness, Shannon-Wiener diversity, Margalef richness, Pielou's evenness, Simpson diversity, and dominance (Table 5). Shannon-Wiener diversity values ranged from 1.57 to 2.67 (Table 5), with the highest value recorded at the non-aquaculture site in Wane (2.67) and the lowest at the non-aquaculture site in Tanjung Mas (1.57). This pattern was consistent with the lower dominance values observed in Wane (0.25-0.31) compared with Tanjung Mas (0.44-0.52), indicating a more even distribution of individuals among taxa in Wane and stronger dominance by a few taxa in Tanjung Mas. The Simpson diversity index exhibited a similar trend, with the highest value recorded at the non-aquaculture site in Wane 0.75 and the lowest at the non-aquaculture site in Tanjung Mas 0.48. Collectively, these three indices consistently positioned Wane and Tanjung Mas at opposite ends of the community-structure gradient.

These characteristics were particularly evident at Wane Beach, which exhibited the most balanced community structure among the three study locations, as indicated by low dominance values (0.25-0.31), high evenness (E: 0.71-0.77), and the highest diversity values (2.36-2.67). This beach also supported the highest macroalgal density, ranging from 39 to 47 individuals m^{-2}. In contrast, Rontu Beach was distinguished by its higher taxa richness, with the highest taxa richness value (11.00) and relatively high Margalef richness values (6.45-6.56), indicating a comparatively large number of taxa relative to the total number of individuals recorded.

An opposite pattern was observed at Tanjung Mas Beach, which exhibited the lowest taxa richness (8.00), the lowest evenness (0.52-0.58), and the highest dominance values (0.44-0.52) among the three study locations. This pattern was accompanied by the lowest macroalgal density, ranging from 20.00 to 23.00 individuals. The lower Simpson Diversity Index values recorded in Tanjung Mas (0.48-0.56), compared with Wane (0.69-0.75) and Rontu (0.62-0.73), further indicate that the community at this location was characterized by stronger dominance of a limited number of taxa (Hajiya-Hasan et al. 2023; Pozas-Schacre et al. 2025).

Overall, these community indices revealed a consistent pattern: Wane and Rontu exhibited higher evenness and lower dominance than Tanjung Mas, indicating a more balanced community structure at both beaches. This variation was consistent with the community patterns observed in the IVI, PCA, and cluster analyses, collectively reflecting spatial heterogeneity in macroalgal community structure across the study locations (Supit et al. 2024; Sombo et al. 2025).

Ordination of sampling locations based on PCA analysis

The Principal Component Analysis biplot showed that the first two principal components explained 90.31% of the total variation in the dataset, with PC1 accounting for 64.44% and PC2 accounting for 25.87% of the variation (Figure 5). Given the six site-level observations, PCA was used as an exploratory tool to visualize ordination patterns and relative similarities among locations. The high proportion of explained variation indicates that most of the variability in the dataset can be represented within a two-dimensional ordination space.

Based on their positions within the ordination space, the Tanjung Mas sites (aquaculture and non-aquaculture) were clearly separated from the other four samples along the PC1 axis, occupying the negative side at a considerable distance from the origin. In contrast, all Wane and Rontu samples were located on the positive side of PC1, although they exhibited a relatively broad dispersion along the PC2 axis. Among these sites, Rontu aquaculture was positioned at the most positive end of PC2, whereas Wane aquaculture occupied the most negative position along the same axis.

Table 5. Community structure metrics of macroalgal assemblages at aquaculture and non-aquaculture sites in the Bima Sea, West Nusa Tenggara, Indonesia

Site	Activity	Wane	Rontu	Tanjung Mas
Density (individuals m^{-2})	Aquaculture	47.00	34.00	23.00
	Non-aquaculture	39.16	36.00	20.00
Taxa richness (TR)	Aquaculture	10.00	11.00	8.00
	Non-aquaculture	11.00	11.00	8.00
Shannon-Wiener diversity (H′)	Aquaculture	2.36	2.16	1.75
	Non-aquaculture	2.67	2.53	1.57
Margalef richness (d)	Aquaculture	5.39	6.56	5.15
	Non-aquaculture	6.28	6.45	5.43
Pielou's evenness (E)	Aquaculture	0.71	0.63	0.58
	Non-aquaculture	0.77	0.73	0.52
Simpson diversity index (1 − D)	Aquaculture	0.69	0.62	0.56
	Non-aquaculture	0.75	0.73	0.48
Simpson dominance index (D)	Aquaculture	0.31	0.38	0.44
	Non-aquaculture	0.25	0.27	0.52

Note: H′: Shannon-Wiener diversity index, d: Margalef richness index, E: Pielou's evenness index (E: H′/ln S); D: Simpson dominance index (D: Σpi^2); 1-D: Simpson diversity index (calculated as 1 minus Simpson dominance index); TR: total taxa richness; S: total number of taxa; pi: proportion of individuals belonging to the i-th taxon

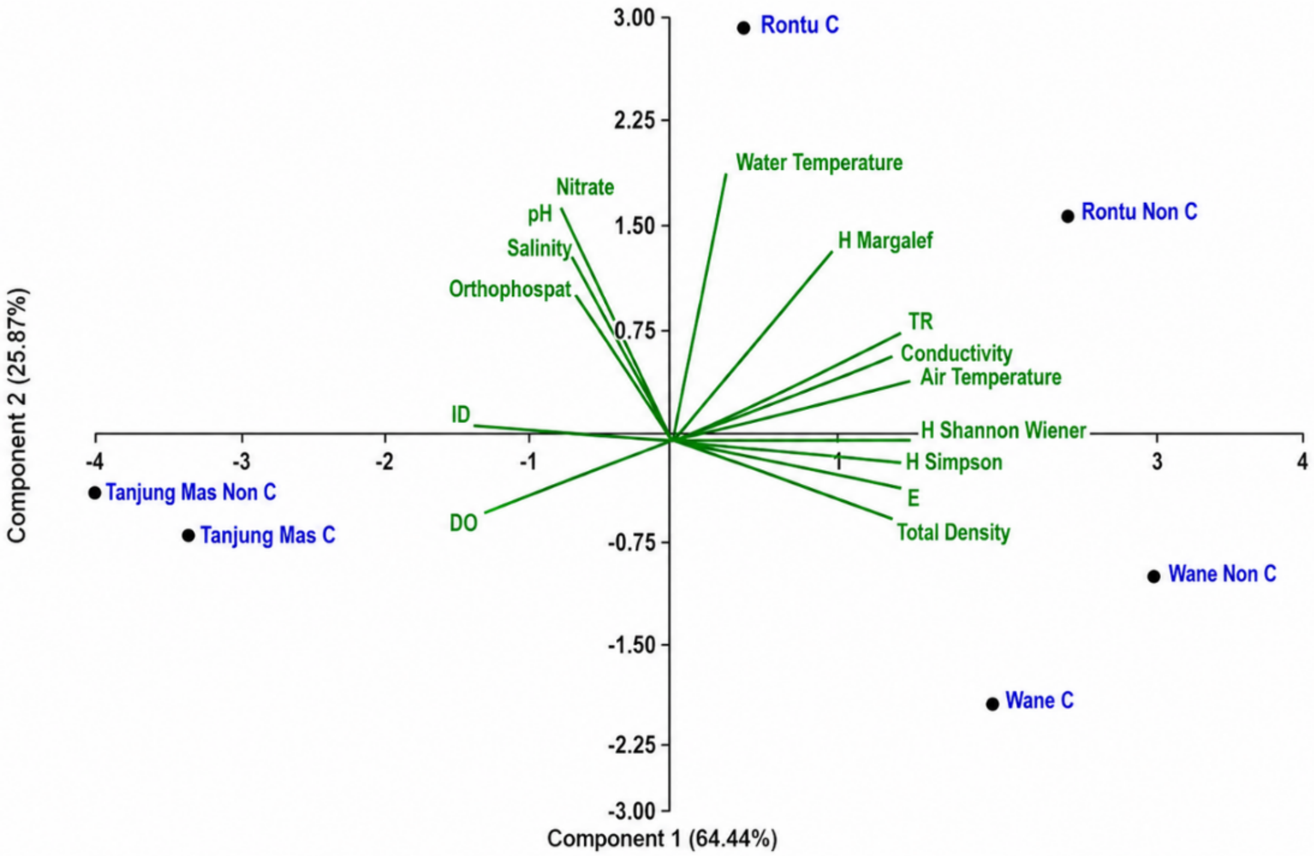

Figure 5. Principal Component Analysis biplot showing the ordination of six sampling locations based on standardized physicochemical parameters and macroalgal community variables in the Bima Sea, West Nusa Tenggara, Indonesia. Location codes indicate management categories: C: aquaculture and Non-C: non-aquaculture. Principal component 1 (PC1) and principal component 2 (PC2) explained 64.44% and 25.87% of the total variance, respectively. The PCA is presented as an exploratory ordination because the analysis was based on six site-level observations

The spatial relationship between aquaculture and non-aquaculture sites within the same beach was not consistent across the three locations. In Tanjung Mas, the aquaculture and non-aquaculture sites occupied very similar positions within the ordination space, indicating nearly identical multivariate characteristics. In contrast, the corresponding site pairs in Rontu and Wane were separated by considerably greater distances, with a comparable degree of separation observed at both beaches. This pattern suggests that multivariate similarity between aquaculture and non-aquaculture areas within the same beach was stronger in Tanjung Mas than in Wane and Rontu.

The PCA was constructed using standardized physicochemical variables, including pH, salinity, dissolved oxygen, nitrate, conductivity, water temperature, and air temperature, together with macroalgal community indices comprising total density, taxa richness, Shannon-Wiener diversity, Simpson diversity, Margalef richness, evenness, and dominance. In the PCA biplot, locations positioned closer together represent more similar multivariate characteristics than locations separated by greater distances within the ordination space (Gumansalangi et al. 2022). The direction and length of the vectors indicate the relative contribution of individual variables to the observed ordination pattern.

Overall, the PCA and cluster analyses revealed consistent patterns of variation in macroalgal communities across the study locations, with the separation of Tanjung Mas from the Wane-Rontu group emerging as the most prominent feature in both analyses. In general, differentiation among beaches was more pronounced than the separation between aquaculture and non-aquaculture areas, although this pattern was most consistently observed in Tanjung Mas compared with Wane and Rontu.

Overall, the results revealed clear spatial variation in macroalgal community structure among the Wane, Rontu, and Tanjung Mas coastal waters. This variation was reflected in differences in taxonomic composition, Importance Value Index values, diversity, evenness, and community dominance among locations. Although nitrate and orthophosphate concentrations consistently exceeded established water-quality reference values across all sites, statistical analyses detected no significant differences among locations for either parameter. Consequently, elevated nutrient concentrations appear to represent a regional characteristic that occurs uniformly throughout the study area rather than a condition specific to any particular location.

Cluster analysis and Principal Component Analysis revealed partially consistent patterns of community similarity and separation among locations, with the distinction between Tanjung Mas and the Wane-Rontu group emerging as the most prominent feature in both analyses. In general, differences in macroalgal community structure among beaches were more pronounced than differences between aquaculture and non-aquaculture categories. However, this pattern was most consistently observed in Tanjung Mas, whereas substantial differences between aquaculture and non-aquaculture areas were also evident in Wane and Rontu. These findings provide a foundation for future studies incorporating broader spatial and temporal coverage to evaluate the consistency of macroalgal community patterns in the Bima Sea.

In conclusion, this study demonstrated clear spatial variation in macroalgal community structure across the coastal waters of Wane, Rontu, and Tanjung Mas in the Bima Sea, West Nusa Tenggara, Indonesia. Macroalgal communities were consistently dominated by *Sargassum* sp. at all locations, whereas diversity, evenness, dominance, and community composition varied among beaches. Nitrate and orthophosphate concentrations exceeded established water-quality reference values throughout the study area but did not differ significantly among locations, indicating that elevated nutrient concentrations represent a uniform regional characteristic of the Bima Sea. The IVI, cluster, and PCA analyses collectively showed that differences in macroalgal community structure were generally more pronounced among beaches than between aquaculture and non-aquaculture areas, although this pattern was most consistently observed in Tanjung Mas. These findings highlight the importance of continuous monitoring of physicochemical water conditions and macroalgal communities as a basis for the sustainable management of tropical coastal ecosystems in the Bima Sea. Further research incorporating broader spatial and temporal coverage is needed to improve understanding of macroalgal community dynamics in this region.

ACKNOWLEDGEMENTS

We sincerely acknowledge the financial support provided by the Center for Higher Education Funding (BPSU) through the Indonesian Education Scholarship Program (BPI), the Center for Higher Education Funding and Assessment (PPAPT), and the Indonesia Endowment Fund for Education Agency (LPDP), Ministry of Finance of the Republic of Indonesia. This research and the doctoral study of the first author were supported under the Indonesian Education Scholarship (BPI), Award Number 00548/BPPT/BPI.06/01/2025. The authors gratefully acknowledge the Laboratory of Ecology and Tropical Ecosystem Restoration, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya; the Laboratory of Plant Physiology, Tissue Culture and Plant Microtechniques, and the Microbiology Laboratory, Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Brawijaya; and the Laboratory of Universitas Nggusuwaru, Indonesia.

REFERENCES

Andini N, Putri N, Sinaga JYN, Juniati Y, Aulia C, Ariyanti I, Febrianti AK, Fathin U, Edelwis TW. 2023. Abundance and distribution of macroalgae in the Nusa Tenggara and their effect on algae blooms. BIO Web Conf 79: 13001. https://doi.org/10.1051/bioconf/20237913001.

Andrew NL, Mapstone BD. 1987. Sampling and the description of spatial pattern in marine ecology. Oceanogr Mar Biol Annu Rev 25: 39-90.

APHA. 2017. Standard Methods for the Examination of Water and Wastewater, 23rd Eds. American Public Health Association, American Water Works Association, and Water Environment Federation, Washington, DC.

Aprilia DH, Santanumurti MB, Jamal MT, Masithah ED, Suciyono. 2023. Diversity, abundance, and distribution of macroalgae in coastal ecotourism areas: A case study at Baluran National Park, Indonesia. Pertanika 46 (1): 11. https://doi.org/10.47836/pjtas.46.1.11.

Atmadja WS, Van Reine WFP. 2014. Checklist of the Seaweed Species Biodiversity of Indonesia. Naturalis Biodiversity Center and LIPI, Jakarta.

Barnes RSK, Mann KH. 2009. Fundamentals of Aquatic Ecology. Wiley, New York.

Basyuni M, Puspita M, Rahmania R, Albasri H, Pratama I, Purbani D. 2024. Current biodiversity status, distribution, and prospects of seaweed in Indonesia: A systematic review. Heliyon 10: e31073. https://doi.org/10.1016/j.heliyon.2024.e31073.

Benhniya B, Lakhdar F, Al-Qoh S, Zidane H, Etahiri S, Rezzoum N. 2024. New checklist of marine macroalgae on the coast of El Jadida, Morocco. Ecol Front 44 (4): 760-768. https://doi.org/10.1016/j.ecofro.2024.02.008.

Boumaiza L, Ammar SB, Chesnaux R, Stotler RL, Mayer B, Huneau F. 2023. Nitrate sources and transformation processes in groundwater of a coastal area experiencing various environmental stressors. J Environ Manag 345: 118803. https://doi.org/10.1016/j.jenvman.2023.118803.

Cannon SE, Donner SD, Liu A, González-Espinosa PC, Baird AH, Baum JK, Bauman AG, Beger M, Benkwitt CE, Birt MJ. 2023. Macroalgae responses to human disturbances on coral reefs. Glob Change Biol 29 (12): 3318-3330. https://doi.org/10.1111/gcb.16694.

Cotas J, Gomes L, Pacheco D, Pereira L. 2023. Ecosystem services provided by seaweeds. Hydrobiology 2 (1): 75-96. https://doi.org/10.3390/hydrobiology2010006.

de Vries J, Kraak MH, Verdonschot RC, Verdonschot PF. 2020. Species composition drives macroinvertebrate community classification. Ecol Indic 119: 106780. https://doi.org/10.1016/j.ecolind.2020.106780.

de Melo-Soares RHR, de Oliveira-Fernandes F, de Assuncao CA, Borburema HDS, do Amaral-Carneiro MA, Marinho-Soriano E. 2023. Macroalgal diversity along an environmental gradient in a saltwork. Estuar Coast Shelf Sci 288: 108377. https://doi.org/10.1016/j.ecss.2023.108377.

Duarte CM, Gattuso JP, Hancke K, Gundersen H, Filbee-Dexter K, Pedersen MF. 2022. Global estimates of the extent and production of macroalgal forests. Glob Ecol Biogeogr 31 (7): 1422-1439. https://doi.org/10.1111/geb.13515.

Duarte RCS, Mota ELS, Dias TLP. 2020. Algal complexity positively affects the abundance, richness and diversity of molluscan assemblages of a semiarid hypersaline mangrove. Aquat Ecol 54: 1001-1013. https://doi.org/10.1007/s10452-020-09789-3.

Fulton CJ, Berkström C, Wilson SK, Abesamis RA, Bradley M, Akerlund C. 2020. Macroalgal meadow habitats support fish and fisheries in diverse tropical seascapes. Fish Fish 21 (4): 700-717. https://doi.org/10.1111/faf.12455.

García-Poza S, Pacheco D, Cotas J, Marques JC, Pereira L, Gonçalves AMM. 2022. Marine macroalgae as a feasible and complete resource to address and promote Sustainable Development Goals (SDGs). Integr Environ Assess Manag 18 (5): 1148-1161. https://doi.org/10.1002/ieam.4598.

Gemilang WA, Wisha UJ, Dhiauddin R. 2019. The importance of nutrients concentration monitoring in coastal area. Ilmu Kelautan 24 (2): 69-80. https://doi.org/10.14710/ik.ijms.24.2.69-80.

Ghazali M, Nurhayati N, Jupri A, Murdiah M. 2024. Keanekaragaman makroalga Pantai Batu Layar, Lombok Barat, Nusa Tenggara Barat. Bioscientist 12 (2): 2595-2607. https://doi.org/10.33394/bioscientist.v12i2.13580. [Indonesian]

Guiry MD. 2010. AlgaeBase. National University of Ireland, Galway, Ireland.

Gumansalangi F, Calle JL, Barea-Sepúlveda M, Manikharda, Palma M, Lideman, Setyaningsih W. 2022. A rapid method for authentication of macroalgae based on Vis-NIR spectroscopy data combined with chemometrics approach. Water 15 (1): 100. https://doi.org/10.3390/w15010100.

Hadiyanto H, Prince J, Hovey RK, Glasby CJ. 2023. Intertidal macroalgal and epiphytic polychaete distributions strengthen marine ecoregions of Western Australia. Front Biogeogr 15 (2): e57954. https://doi.org/10.21425/F5FBG57954.

Hajiya Hasan AH, Al-Bader DA, Woodward S, Peters AF, Küpper FC. 2023. Ecophysiology of Kuwaiti macroalgae with special emphasis on temperature and salinity tolerance related to the conditions at desalination plant outfalls. Bot Mar 66 (5): 373-390. https://doi.org/10.1515/bot-2022-0049.

Halabowski D, Lewin I. 2020. Impact of anthropogenic transformations on the vegetation of selected abiotic types of rivers in two ecoregions (Southern Poland). Knowl Manag Aquat Ecosyst 421: 35. https://doi.org/10.1051/kmae/2020026.

Hamzah R, Hakim L, Retnaningdyah C. 2020. Evaluation of the quality of coastal ecosystems in the Spermonde Archipelago using macroalgae as indicators. J Trop Life Sci 10 (2): 113-122. https://doi.org/10.11594/jtls.10.02.04.

Handayani S, Widhiono I, Widyartini DS. 2023. Macroalgae diversity in polluted waters of Jakarta Bay. Biodiversitas 24 (11): 6279-6286. https://doi.org/10.13057/biodiv/d241151.

Hanley ME, Firth LB, Foggo A. 2024. Victim of changes? Marine macroalgae in a changing world. Ann Bot 133 (1): 1-16. https://doi.org/10.1093/aob/mcad185.

Innocenti RA, Feagin RA, Huff TP. 2018. The role of *Sargassum* macroalgal wrack in reducing coastal erosion. Estuar Coast Shelf Sci 214: 82-88. https://doi.org/10.1016/j.ecss.2018.09.021.

Krause-Jensen D, Duarte CM. 2016. Substantial role of macroalgae in marine carbon sequestration. Nat Geosci 9 (10): 737-742. https://doi.org/10.1038/ngeo2790.

Martin LM, Taylor M, Huston G, Goodwin DS, Schell JM, Siuda ANS. 2021. Pelagic *Sargassum* morphotypes support different rafting motile epifauna communities. Mar Biol 168 (7): 115. https://doi.org/10.1007/s00227-021-03910-2.

Pelasula DD, Wouthuyzen S, Waileruny W, Rubamlifar A, Hukom FD, Matuankota C. 2023. Changes of coastal ecosystems in East Seram District, Maluku Province, Indonesia and their impact on Julung-julung fish (*Hemirhamphus* sp.) resources. Intl J Conserv Sci 14 (1): 265-280. https://doi.org/10.36868/IJCS.2023.01.18.

Pessarrodona A, Assis J, Filbee-Dexter K, Burrows MT, Gattuso JP, Duarte CM. 2022. Global seaweed productivity. Sci Adv 8 (37): eabn2465. https://doi.org/10.1126/sciadv.abn2465.

Pozas-Schacre C, Bischoff H, Raviglione D, Chaib S, Clerissi C, Bonnard I, Maggy MN. 2025. Invasive macroalgae shape chemical and microbial waterscapes on coral reefs. Commun Biol 8 (1): 16. https://doi.org/10.1038/s42003-024-07433-6.

Rahmadi P, Sjafrie NDM, Rizqi MP, Triyono, Handayani T, Kusnadi A, Duan D, Dirhamsyah, Hernawan UE, Pangestuti R. 2025. Challenges and opportunities in seaweed (Eucheumatoids) cultivation in Indonesia: A review and strategic recommendations. Aquacult Intl 33 (7): 680. https://doi.org/10.1007/s10499-025-02336-7.

Rasyid A, Putra MY, Handayani W. 2025. Macroalgal community structure and beta diversity in the coastal waters of East Lombok, Indonesia. Biodiversitas 26 (7): 3115-3124. https://doi.org/10.13057/biodiv/d260703.

Salvanes AGV, Jensen KH. 2018. Marine Ecological Field Methods. Wiley, Hoboken.

Shannon CE, Weaver W. 1949. A Mathematical Model of Communication. University of Illinois Press, Urbana.

Short FT, Coles RG. 2001. Global Seagrass Research Methods. Elsevier, Amsterdam.

Silva PC, Basson PW, Moe RL. 1996. Catalogue of the Benthic Marine Algae of the Indian Ocean. University of California Press, Berkeley.

Sjafrie NDM, Rahmadi P, Triyono, Kurniawan F, Supriyadi IH, Zulpikar F, Adrianto L, Rahmawati S, Hernawan UE. 2024. Monetary value of ecosystem services in unhealthy seagrass meadows in Indonesia. Ecosyst Serv 70: 101668. https://doi.org/10.1016/j.ecoser.2024.101668.

Solihuddin T, Husrin S, Mustikasari E, Heriati A, Kepel TL, Salim HL, Risandi J, Dwiyanti D. 2021. Coastal inundation and land subsidence in north coast of West Java: A new hazard? IOP Conf Ser Earth Environ Sci 925 (1): 012015. https://doi.org/10.1088/1755-1315/925/1/012015.

Sombo IT, Arisoesilaningsih E, Sartimbul A, Kurniawan N, Retnaningdyah C. 2025. Seagrass diversity profile and water quality in some coastal ecosystems in East Nusa Tenggara, Indonesia. Biodiversitas 26 (11): 5931-5943. https://doi.org/10.13057/biodiv/d261148.

Stiger-Pouvreau V, Zubia M. 2020. Macroalgal diversity for sustainable biotechnological development in French tropical overseas territories. Bot Mar 63 (1): 17-41. https://doi.org/10.1515/bot-2019-0032.

Sukarni, Hartati, Azmin N. 2025. Evaluation of beach ecosystems in Monta District, Bima Regency using macroalgae as an indicator of marine tourism development. J Penelitian Pendidikan IPA 11 (9): 407-415. https://doi.org/10.29303/jppipa.v11i9.12521.

Supit RRL, Emola IJ, Ginzel FI. 2024. Struktur komunitas makroalga di daerah intertidal pantai berbatu Desa Otan, Kecamatan Semau, Kabupaten Kupang, Provinsi Nusa Tenggara Timur. J Mar Res 13 (3): 577-586. https://doi.org/10.14710/jmr.v13i3.43836. [Indonesian]

Trono GC. 1997. Field Guide and Atlas of the Seaweed Resources of the Philippines. Bookmark Inc., Makati City.

Wilhm JL, Dorris TC. 1968. Biological parameters for water quality criteria. BioScience 18 (6): 477-481. https://doi.org/10.2307/1294272.

Zulpikar F, Handayani T. 2021. Life form, diversity, and spatial distribution of macroalgae in Komodo National Park waters, East Nusa Tenggara. IOP Conf Ser Earth Environ Sci 944 (1): 012026. https://doi.org/10.1088/1755-1315/944/1/012026.