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Seasonal changes on macroalgae community structure on the South Coast of Yogyakarta, Indonesia

Ratih Ida Adharini[1]*, Kim Hyung Geun[2], Eko Setyobudi[1], Endah Prihatiningtyastuti, Namastra Probosunu, Sulistiowati[1] and Eko Hardianto[1]

[1]Department of Fisheries, Faculty of Agriculture, Universitas Gadjah Mada. Jl. Flora Bulaksumur, Depok, Sleman, Yogyakarta, Indonesia 55281

[2]Department of Marine Ecology and Environment, Gangneung-Wonju National University, Gangwon, 25457. Republic of Korea

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*to whom all correspondence should be addressed: e-mail: ratih.adharini@ugm.ac.id

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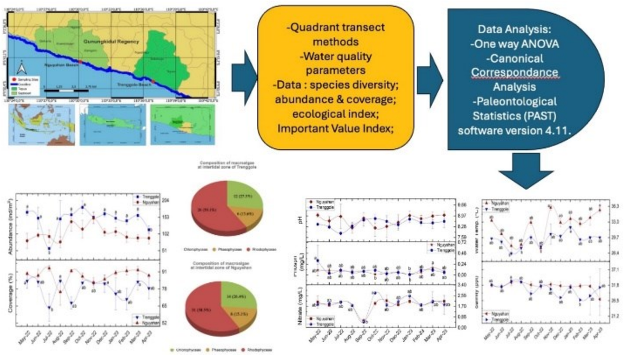
Graphical abstract



Abstract

The environmental conditions significantly influence the dynamics of macroalgae community structure and distribution. This study investigates the effects of seasonal changes on the macroalgae community structure and distribution along the South Coast of Yogyakarta. The study was conducted over twelve months in two intertidal zones, Trenggole and Nguyahan, using the transect method with plots. Monthly rainfall data and water quality parameters were collected as supporting data. The data were analyzed using ANOVA, and the relationship between water quality and community structure was determined using Canonical Component Analysis (CCA). The results indicated a moderate diversity index (1.05-2.71) and a low dominance index (0.02-0.37). The average abundance at Trenggole (145.74 ind. m^{-2}) was higher than at Nguyahan (103.72 ind. m^{-2}). The percentage coverage at Trenggole (67.71%) was lower than at Nguyahan (88.14%). Seaweed abundance and percentage cover were relatively higher during the wet season than in the dry season. The diversity of macroalgae tended to be higher in the rainy season than in the dry season. Seasonal changes significantly affected macroalgae abundance and coverage at Trenggole, whereas at Nguyahan, the distance from the shoreline showed significant differences. Temperature, salinity, and pH were the most influential factors affecting the macroalgae community structure. Additionally, coastal characteristics, distance from the shoreline, and substrate types played a pivotal role in shaping the macroalgae community structure. Rhodophyceae species were the most dominant, followed by Chlorophyceae and Phaeophyceae, on the South Coast of Yogyakarta.

Keywords: seasonal changes, coverage, density, diversity, shoreline, Rhodophyceae

1. Introduction

Macroalgae are integral components of intertidal ecosystems, alongside seagrass and coral reef ecosystems. They play a pivotal role in providing essential ecosystem services, such as serving as habitats for various biota, functioning as primary producers in food webs, participating in nutrient cycling, and contributing to carbon sequestration. According to Jung *et al.* (2019), areas with high macroalgae diversity support greater zoobenthic and fish diversity. Additionally, tropical macroalgae contribute to the blue carbon ecosystem (Kwan *et al.* 2022). The diversity of macroalgae holds significant potential for human and animal consumption, the production of seaweed-based products, and the provision of ecological services (Radulovich *et al.* 2015; Stiger-Pouvreau and Zubia, 2020; Olsson *et al.* 2020).

Seasonal changes, environmental parameters, shoreline characteristics, and substrate types can all influence the distribution and community structure of macroalgae, subsequently affecting their ecological functions within ecosystems. The South Coast of Yogyakarta, characterized by a substrate of dead coral substrate and white sand, provides a suitable habitat for various macroalgae species. The type of substrate has been reported to affect benthic macroalgae communities (Tsiamis *et al.* 2020). In this region, the macroalgae ecosystem continues to thrive naturally, with distribution, abundance, species composition, and ecological indices influenced by both natural and anthropogenic factors, as well as biotic and abiotic factors.

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Several studies have shown that the dynamics of biomass, population, and productivity of macroalgae are influenced by variations in climate and season, temperature, rainfall, and sunlight (Sanz *et al.* 2023; Jansen *et al.* 2022). Environmental stress levels, including those induced by tourism activities, can also affect the growth and population of macroalgae (Gaspar *et al.* 2017; Mayakun and Prathep, 2005). Furthermore, competition among species can impact macroalgae abundance (Yoshida and Shimabukuro, 2017), and anthropogenic factors, such as the introduction of species into intertidal areas, can alter macroalgae composition and diversity (Raffo *et al.* 2014; Mantri *et al.* 2020). Baseline data on the community structure and abundance of macroalgae in intertidal zones are essential for monitoring the impacts of climate change (Piñeiro-Corbeira *et al.* 2023). Several studies stated that the diversity of macroalgae on the south coast of Gunungkidul is categorized as having low to moderate diversity (Riswanti and Santosa 2017; Sodiq and Arisandi 2020). However, no research has been conducted on the seasonal changes in macroalgae community structure on the South Coast of Yogyakarta. Therefore, this study is necessary to establish a database that will support coastal area management and ensure the sustainability of the ecological and economic functions of macroalgae resources in this region.

2. Materials and methods

2.1. Study location and time of research

The study was conducted on the South Coast of Yogyakarta, Indonesia, focusing on two intertidal zones: Trenggole and Nguyahan. These locations were selected as they are representative of the coastal conditions in the southern region of Yogyakarta, as shown in Figure 1. The research was conducted from May 2022 until April 2023.

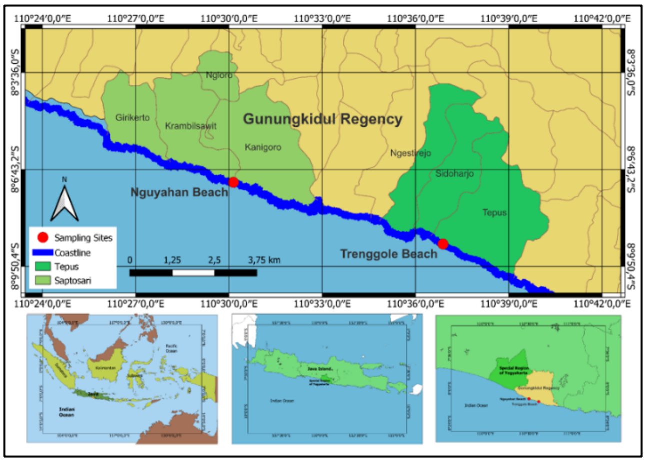

Figure 1. Study sites on the South Coast of Yogyakarta, Indonesia

2.2. Methods

2.2.1. Sampling of macroalgae

The ecological index of seaweed in the intertidal zone of Trenggole and Nguyahan was estimated through several steps, including location determination using the quadrant transect method with 1 × 1 m plots divided into 16 grids. Data were collected at 9 points, consisting of 3 stations, with each station containing 3 substation points. Line transects were drawn at 10 m, 20 m, and 30 m from the shoreline for data collection.

2.2.2. Abundance and coverage of macroalgae

Abundance (ind. m^{-2}) is used to calculate the density of individuals or colonies in an ecosystem. Abundance was calculated using the formula by English *et al.* (1997):

$$\text{Abundance} = \frac{\text{Number of individual or colonies}(n)}{\text{total plot area}(A)} \qquad (1)$$

Coverage of macroalgae in this study was calculated using the approach by English *et al.* (1997):

$$\text{Coverage} = \frac{\text{Number of grids filled with macroalgae}}{\text{Total number of grids in the observation plots}} \times 100\% \qquad (2)$$

The total number of observation fields per point was 16, corresponding to a plot size of 1 x 1 m divided into 16 grids.

2.2.3. Determining the species of macroalgae

Macroalgae samples from each plot were placed into labeled plastic bags for identification and documentation. The species were identified morphologically by Guiry and Guiry (2023) on the Algaebase website (www.algaebase.org).

2.2.4. Shannon-Wiener (H') diversity index

The species diversity index of macroalgae was calculated using the Shannon-Wiener diversity index formula (Krebs, 1983):

$$H' = -\sum_{i=1}^{n} Pi \ln Pi \qquad (3)$$

where H' is the Shannon-Wiener diversity index, *Pi* is the proportion of individuals of species *i* (n_i/N), n_i is the number of individuals of a species *i*, *N* is the total number of individuals, and *s* is the number of species per location.

The diversity index values are interpreted as follows (Krebs, 1983):

$H' < 1$: low species diversity

$1 \le H' \le 3$: moderate species diversity

$H' \ge 3$: high species diversity

2.2.5. Evenness Index (E)

The evenness index (E) indicates uniformity and abundance distribution among species. The formula by Krebs (1983) is:

$$E = \frac{H'}{H\max} \qquad (4)$$

where E is the evenness index, *H'* is the diversity index; *Hmax* is the maximum uniformity (Ln S), and *S* is the number of species found.

The evenness index values are interpreted as follows (Krebs, 1983):

$0 < E \le 0.4$: the community is in a depressed state

$0.4 < E \le 0.6$: the community is in an unstable state

$0.6 < E \le 1$: the community is in a stable condition

2.2.6. Dominance Index (C)

The dominance index was calculated using the Simpson dominance index formula by Odum (1993):

$$C = \sum_{i-1}^{s} (Pi)^2 \qquad (5)$$

where C is the dominance index, Pi is the proportion of individuals of species i (ni/N), n_i is the number of species i, N is the total number of individuals, and s is the number of species.

The dominance index values are interpreted as follows (Odum, 1993):

$0 < C \leq 0.50$: low dominance

$0 < C \leq 0.50$: medium dominance

$0.75 < C \leq 100$: high dominance

2.2.7. Important Value Index (IVI) of macroalgae

The Important Value Index (IVI) is used to estimate and calculate the role of seaweed species in a community structure. The IVI was calculated using the formula by Brower *et al.* (1998):

$$\text{IVI} = \text{Relative density} + \text{relative frequency} + \text{relative coverage} \tag{6}$$

$$\text{Relative density} = \frac{\text{Density of a particular species } (ni)}{\text{Total density of all species } (\Sigma n)} \times 100\% \tag{7}$$

$$\text{Relative frequency} = \frac{\text{Frequency of a particular species } (ni)}{\text{Total frequency of all species } (\Sigma F)} \times 100\% \tag{8}$$

$$\text{Relative coverage} = \frac{\text{Area of cover of a particular species } (Ci)}{\text{Total cover area of all species } (\Sigma Ci)} x 100\% \tag{9}$$

2.2.8. Water quality parameters

Environmental parameters, including water temperature, salinity, and pH, were measured using a water quality checker (Hanna Instruments HI98194). Nitrate and phosphate content were measured using a spectrophotometer (APHA 2017).

2.3. Data analysis

Data from the monthly calculations of frequency, density, coverage, and important value indices were processed using Microsoft Excel and subsequently analyzed with one-way ANOVA. The purpose of the significant difference analysis was to determine the monthly ecological index differences of macroalgae between Trenggole and Nguyahan Beaches. Additionally, the results of water quality measurements were analyzed to assess significant differences in relation to monthly changes in ecological and environmental indices. Canonical Correspondence Analysis (CCA) was employed to explore the multivariable relationship between water quality and species' ecological data. This analysis was conducted using Paleontological Statistics (PAST) software version 4.11 (Hammer, 2022).

3. Results and Discussion

3.1. Species composition of macroalgae

During the research period, 44 species of macroalgae were identified at Trenggole, while 53 species were found at Nguyahan. The composition of macroalgae communities was dominated by Rhodophyceae (>50%), followed by Chlorophyceae (>25%), and the remainder being Phaeophyceae (Figure 2). These findings align with those from other countries, where species from Rhodophyceae are more abundant than those from Phaeophyceae and Chlorophyceae (Oh *et al.* 2016; Kokabi *et al.* 2016; Dangar *et al.* 2022). Prather (2005) also noted that tropical regions typically exhibit a higher diversity of red seaweeds than temperate regions. However, Chlorophyceae and Phaeophyceae exhibited higher abundance and coverage when compared to Rhodophyceae, mainly in the mid and high-intertidal zones, whereas Rhodophyceae were predominantly found in low-intertidal areas.

The species of macroalgae found at both sites during the study period are listed in Table 1 and illustrated in Figure 2 and 3.

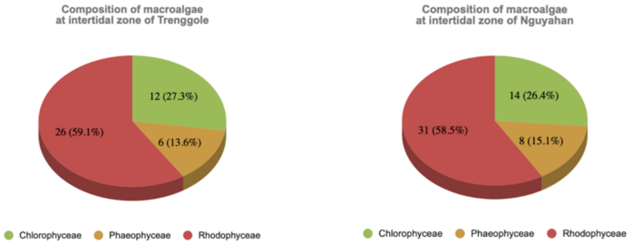

Figure 2. Macroalgae composition in the South Coast of Yogyakarta

Species such as *Ulva lactuca*, *Chaetomorpha linum*, *Chaetomorpha viellardii*, *Sargassum polycystum*, *Pterocladiella* sp., and *Gelidiella acerossa* were the most common across both study sites (Figure 3). This is likely due to the relatively similar environmental conditions at both beaches, despite slight differences in beach characteristics. The fertile conditions at both locations allow species with a broad tolerance to environmental changes to grow optimally and abundantly (Hoang *et al.* 2016; Zou *et al.* 2017). *Ulva* sp. and *Sargassum* sp. are widespread and occur throughout the seasons in the intertidal areas of Argentina Patagonia (Raffo *et al.* 2014), Korea (Oh *et al.* 2016; Ahn *et al.* 2017), Thailand (Mayakun and Prathep, 2005), and the northern coast of Persian Gulf (Dadolahi-Sohrab *et al.* 2012). This widespread occurrence is likely due to the high tolerance and adaptability of Ulva and Sargassum to environmental changes, which contributes to their extensive distribution. Ulva is particularly adaptable to environmental changes and can efficiently absorb nutrients, resulting in a high growth rate and productivity (Adharini *et al.* 2021; Toth *et al.* 2020). Meanwhile, Sargassum demonstrates resilience in the environment due to its high tolerance to epiphytic disturbances, fouling, and threats from herbivorous fish (Radulovich *et al.* 2015).

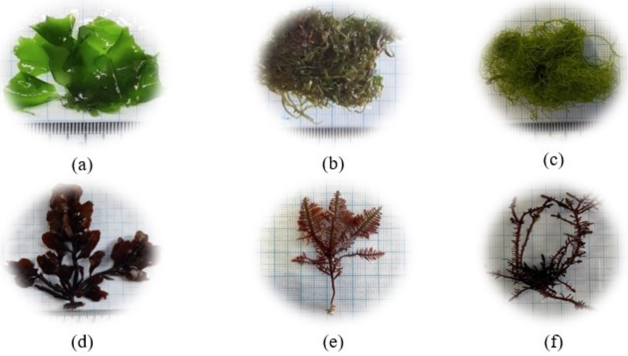

Figure 3. The most common species of macroalgae found at the study sites, (a) *Ulva lactuca*, (b) *Chaetomorpha linum*, (c) *Chaetomorpha viellardii*, (d) *Sargassum polycystum*, (e) *Pterocladiella* sp.; (f) *Gelidiella acerossa*

Table 1. The species of macroalgae found on study sites

Species of macroalgae on Trenggole	**Species of macroalgae on Nguyahan**
Chlorophyceae:	**Chlorophyceae:**
Boergesenia forbesii	*Boergesenia forbesii*
Bryopsis Rhizophora M.Howe 1914	*Bryopsis Rhizophora*
Caulerpa racemose	*Caulerpa racemose*
Chaetomorpha antenna (Bory) Kutzing	*Chaetomorpha antenna*
Chaetomorpha crassa	*Chaetomorpha ligustica*
Chaetomorpha ligustica	*Chaetomorpha linum*
Chaetomorpha ligustica	*Chaetomorpha viellardii*
Chaetomorpha viellardii	*Cladophoriopsis javanica*
Ulva sp.	*Enteromorpha compressa*
Ulva fasciata	*Enteromorpha flexuosa*
Ulva fasciata	*Ulva meridionalis*
Ulva rigida	*Ulva fasciata*
	Ulva lactuca
	Ulva sp.
Phaephyceae:	**Phaeophyceae:**
Padina australis	*Dictyota ciliolate*
Padina boryana	*Dictyota sp.*
Padina boryana	*Padina australis*
Sargassum aquifolium (Turner) C. Agardh 1820	*Padina minor*
Sargassum polycystum C. Agardh	*Sargassum aquifolium*
Sargassum yinggehaiense Tseng & Lu 2002	*Sargassum polycystum*
	Sargassum yinggehaiense
	Turbinaria sp.
Rhodophyceae:	**Rhodophyceae:**
Acanthophora spicifera	*Acanthophora spicifera*
Acrocystis nana Zanardini	*Acrocystis nana*
Amphiroa fragilisima	*Ahnfeltiopsis fastagiata*
Callophyllis crispata Okamura	*Amphiroa fragilisima*
Callophyllis crispata Okamura	*Callophyllis crispate*
Ceramium japonicum Okamura	*Ceramium sp.*
Chondrus crispus	*Chondrophycus sp.*
Gelidiella acerosa	*Chondrus sp*
Gelidiella fanii	*Gelidiella acerosa*
Gelidium indonesianum	*Gelidiella fanii*
Gigartina polycarpa	*Gelisium pussilum*
Gracilaria arcuate	*Pterocladiella sp.*
Gracilaria corticata J. Agardh	*Gelidium indonesianum*
Gracilaria edulis	*Gelidiopsis sp.*
Gracilaria multipartite	*Gelidium japonicum*
Gracilaria Salicornia	*Gigartina polycarpa*
Gracilaria verrucose	*Gracilaria arcuate*
Gracilaria vieillardii	*Gracilaria corticate*
Halymenia maculate	*Gracilaria edulis*
Halymenia floresi	*Gracilaria multipartite*
Hypnea asiatica	*Gracilaria Salicornia*
Laurencia brongniartii	*Gracilaria verrucosa*
Laurencia intermedia	*Gracilaria vieillardii*
Laurencia papillosa	*Halymenia maculate*
Mastocarpus papilatusHypnea sp.	*Hypnea nidulans*
Pterocladiella sp	*Hypnea pannosa*
	Laurencia brongniartii
	Laurencia intermedia
	Laurencia obtuse
	Laurencia papillosa
	Palisada concreta

Rhodymenia palmata

Description: Classification reference: Algaebase (2023)

3.2. Dynamics of Coverage and abundance of macroalgae

The abundance and coverage of macroalgae at the study sites showed seasonal variation. However, macroalgae abundance at Trenggole was higher than at Nguyahan, while macroalgae coverage at Nguyahan tended to be greater than at Trenggole (Figure 4).

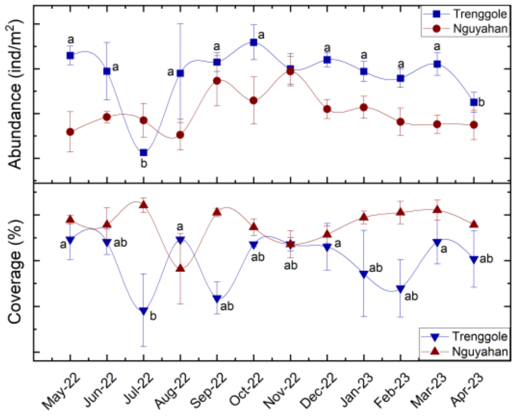

Figure 4. Seasonal changes of macroalgae coverage and abundance in Treggole (TRL) and Nguyahan (NGU)

The abundance and coverage of macroalgae at Trenggole underwent significant seasonal changes. Abundance showed considerable fluctuations, with an average of 145.74 ind. m^{-2}, peaking in October 2022. Similarly, the coverage of the macroalgae community in this location fluctuated throughout the study, reaching its highest value of 67.71% in August 2022. Spatially, the abundance and coverage of seaweed communities at different observation distances showed no significant differences. The highest abundance of seaweed was recorded 20 meters from the shoreline, with an average of 180.42 ind. m^{-2}, while the highest coverage was observed 10 meters from the shoreline, with an average of 80.90% (Figure 5).

In contrast, the abundance and coverage of macroalgae communities at Nguyahan showed insignificant temporal fluctuations but exhibited significant differences based on distance from the shoreline. Seaweed abundance and coverage were relatively higher during the wet season compared to the dry season. The average abundance at Nguyahan was 103.72 ind. m^{-2}, with the highest abundance recorded in November 2022. Meanwhile, macroalgae coverage reached an average of 88.14%, peaking in July 2022. Prather (2005) noted that factors such as season, wave exposure, shore elevation, and species interactions influence seaweed percentage cover. Seasonal macroalgae growth also depends on their ability to tolerate drought and varying environmental conditions (Adharini *et al.* 2016).

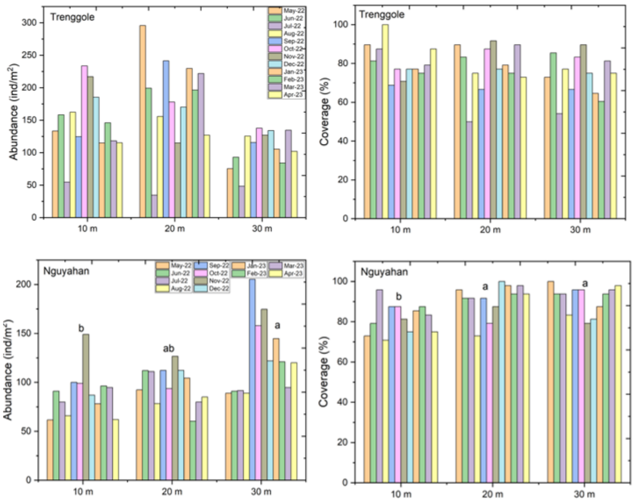

Figure 5. The dynamics of abundance and coverage of macroalga by temporal and distance from the shoreline.

Table 2. Important Value Index (IVI) of macroalgae in the intertidal zone of Trenggole and Nguyahan

Species of macroalgae	Sites	Relative frequency (%)	Relative density (%)	Relative coverage (%)	IVI (%)
Ulva lactuca	Trenggole	17,98	35,65	37,42	91,04
	Nguyahan	7,78	10,52	10,52	28,81
C. linum	Trenggole	8,90	10,95	9,69	29,54
C. viellardii	Nguyahan	11,14	24,93	24,93	60,99
S. polycystum	Trenggole	10,70	12,45	14,15	37,30
	Nguyahan	1,31	0,35	0,35	2,01
Pterocladiella sp.	Trenggole	5,90	8,21	9,12	23,23
	Nguyahan	3,25	7,88	7,88	19,01
Acrocytis nana	Trenggole	5,62	6,17	6,17	17,96
G. acerosa	Nguyahan	8,26	9,13	9,13	26,52
Others	Trenggole	50,90	26,57	23,45	100,93
	Nguyahan	68,28	47,19	47,19	162,65

The highest abundance and coverage of macroalgae were found 30 meters from the shoreline (Figure 5). These findings are supported by Raffo *et al.* (2014), who stated that both season and distance or depth from the intertidal zone strongly influence the species composition of macroalgae. In general, the lower the intertidal zone, the greater the species diversity compared to the higher intertidal zone (Kokabi *et al.* 2016). In both Trenggole and Nguyahan, Chlorophyceae were found in the shallowest waters of the coastal intertidal zone, at distances of approximately 10 meters from the shoreline. The presence of Chlorophyta species in these shallow waters may be attributed to the sand substrate and coral rubble along the intertidal zone (Handayani *et al.* 2023). Phaeophyceae, on the other hand, were observed growing firmly attached to coral or rocky substrates at distances of around 20 meters from the shoreline. Xu *et al.* (2016) reported that attachment strength is generally greater in shallow waters than in deeper areas. In this study, many Rhodophyceae were found growing submerged in deeper basins (lagoons) approximately 30 meters from the shoreline. Rhodophyceae can thrive in deeper waters due to their auxiliary photosynthetic pigments, which enable them to absorb sunlight for photosynthesis. This contrasts slightly with conditions on the tropical west coast of Africa, where Phaeophyceae are more commonly found in the upper intertidal zone, Rhodophyceae in the middle intertidal, and Chlorophyceae are less frequently encountered (Piñeiro-Corbeira *et al.* 2023).

3.3. Important Value Index (IVI)

The important value index (IVI) of macroalgae in the intertidal zones of Trenggole and Nguyahan exhibited dynamic variation throughout the year (Table 2).

The macroalgae species that played the most significant role in the seaweed community at Trenggole during the study was *Ulva lactuca*, followed by *Sargassum polycystum*, *Acrocytis nana*, and *Pterocladiella* sp. In contrast, at Nguyahan Beach, *Chaetomorpha Viellardii* had the most significant role, followed by *Ulva lactuca*, *Pterocladiella* sp., and *Gelidiella acerosa*. According to Khudin *et al.* (2019), the higher a species's IVI, the greater its role in the community.

3.3.1. Diversity, evenness, and dominance index of macroalgae

Seasonal changes in macroalgae diversity at the study site indicated moderate levels of diversity (Figure 6) and low levels of dominance (Figure 8), while the evenness index showed fluctuations throughout the study period (Figure 7).

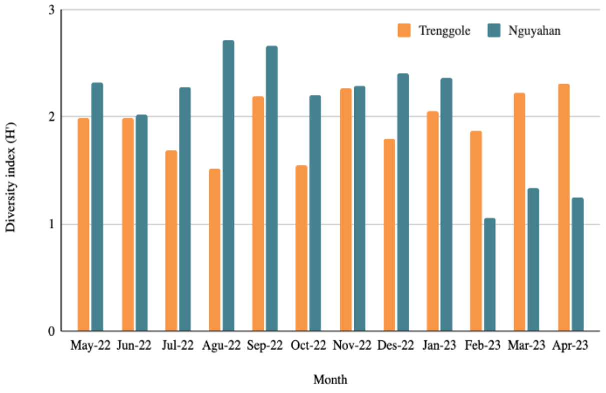

Figure 6. Seasonal changes of macroalgae diversity index (H') on study sites

The macroalgae diversity index in Trenggole averaged 1.95, while the diversity index (H) in Nguyahan averaged 2.07, indicating moderate diversity in both intertidal zones. However, the diversity index in Nguyahan was slightly higher than in Trenggole. This could be due to Nguyahan having more basins, a longer and more exposed coastline, and a stable intertidal zone with abundant dead coral substrate, making it a suitable habitat for a variety of macroalgae species. Intertidal zones with numerous deep basins provide ideal habitats for red algae species that require greater depth, while a long shoreline minimizes intraspecific and interspecific competition for substrate attachment. Nguyahan, with its exposed rocky coastline and dead coral substrate, offers a favorable environment for various macroalgae, as some species require a rigid substrate to anchor their holdfasts. Wells *et al.* (2007) noted that beaches with rock ridge substrates have the highest macroalgae diversity, followed by rock boulders, steep rocks, pebbles, and gravel.

Erniati *et al.* (2023) highlighted that seaweed community diversity is influenced by internal factors such as competition for space and nutrients, as well as external factors like environmental pollution, exploitation of fishery resources, and low biological productivity. Seaweed diversity was higher during the rainy season (September 2022 – January 2023) than in the dry season (Figure 6). In contrast, Prather (2005) reported that in Phuket, Thailand, seaweed diversity was higher during the dry season, when wave activity was calmer.

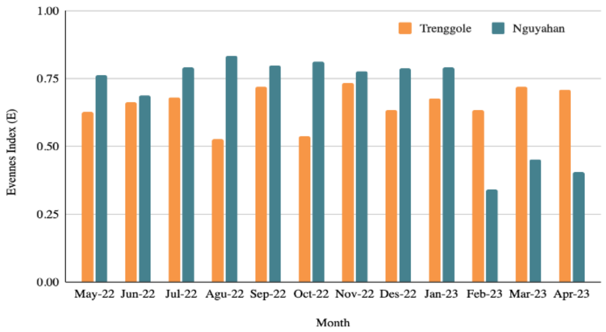

Figure 7. Seasonal changes of macroalgae Evenness index (E) in the study site

The evenness index (E) of macroalgae at Nguyahan averaged 0.69, indicating stable macroalgae conditions from May 2022 to January 2023. Meanwhile, the evenness index at Trenggole averaged 0.65 (Figure 7). However, in August and October 2022, macroalgae in Trenggole exhibited unstable conditions in terms of uniformity. A lower evenness index suggests that the community experienced dominance by certain species that were more resilient to environmental changes.

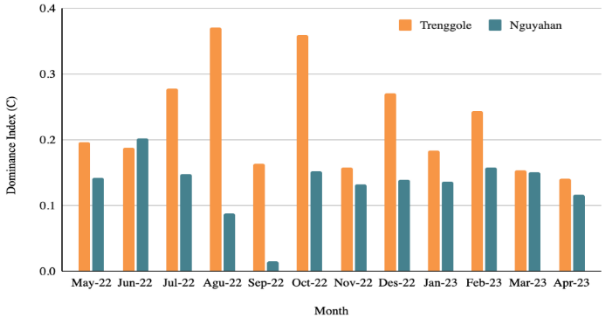

Figure 8. Seasonal changes of macroalgae dominance index (C) in the study site

The average dominance index in Trenggole was 0.23, while in Nguyahan, it averaged 0.13, indicating low macroalgae dominance across the study sites (Figure 8). The dominance index in Trenggole was higher due to its lower diversity and evenness compared to Nguyahan. In general, the higher the diversity and evenness indices, the lower the dominance index, which in turn supports the stability and resilience of an ecosystem against disturbances.

3.4. Seasonal Changes in Water Quality Parameters

The spatio-temporal variations in water quality parameters at the study site are presented in Figure 9.

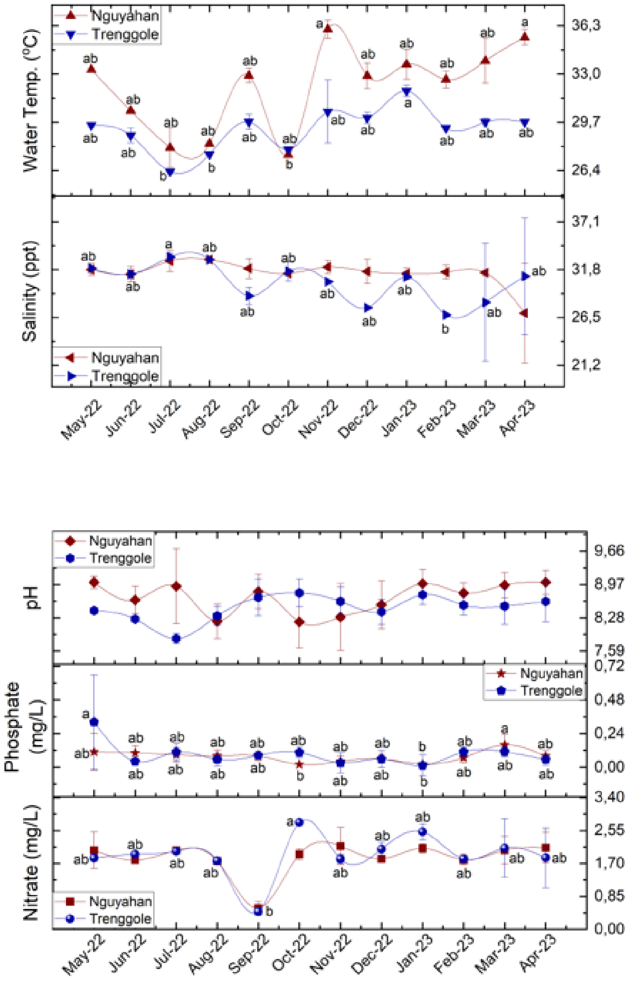

Figure 9. Seasonal changes in precipitation and water quality parameters in the study site

Daily rainfall in the southern coastal area of Yogyakarta fluctuated between 0.10 and 27.60 mm, with an average rainfall of 10.10 mm. According to Sanz *et al.* (2023), months with high solar radiation support macroalgae growth and influence biochemical compounds and phycobiliprotein levels. The monthly variations in water temperature at both sites showed dynamic conditions, though the temperature range remained suitable for sustaining various macroalgae species. In this study, the abundance and coverage of macroalgae is relatively high in the transition of the rainy season to the beginning of the dry season. Tropical seaweed generally grows optimally at the temperature range between 25 and 35°C (Widyartini *et al.* 2017). Temperature directly influences enzymatic reactions involved in photosynthesis, with higher temperatures increasing the rate of photosynthesis. Water temperature is a significant factor in seaweed growth, as it affects dissolved oxygen levels and photosynthetic processes (Haas *et al.* 2014).Salinity at both study sites showed significant fluctuations, but it remained within a range that supports macroalgae life. Optimal seaweed growth generally occurs in salinities between 28 and 34 ppt (Madina *et al.* 2022). Water salinity affects the osmoregulation process, which is essential for the growth and development of macroalgae. Seawater pH in the intertidal zone of Nguyahan ranged from 8.20 to 9.02, while at Trenggole, it ranged from 7.85 to 8.80. These pH levels are conducive to the optimal growth of various seaweed species. The degree of acidity (pH) is linked to hydrogen ion activity in the water. In alkaline conditions, a higher percentage of un-ionized ammonia is present, which can enhance the rate of photosynthesis in macroalgae.

Nitrate levels at Nguyahan fluctuated stably, with an average of 1.8 mg/L, while Trenggole showed more significant fluctuations, averaging 1.91 mg/L. According to Boyd (1982), the tolerance limit for nitrate in algae growth is between 0.1 and 3 ppm, indicating that nitrate levels at both sites are within the optimal range to support seaweed growth. Phosphate levels averaged 0.08 mg/L at Nguyahan and 0.09 mg/L at Trenggole, both of which are sufficient for promoting seaweed growth. Nutrients such as nitrate and phosphate influence the fatty acid, protein, and phenolic content of macroalgae (Toth *et al.* 2020).

3.5. Relationship of Water Quality to Important Value Index (IVI) of macroalgae

Water quality measurements on the South Coast of Yogyakarta during the study revealed dynamic changes that significantly impacted the community structure of macroalgae (Figures 10 and 11).

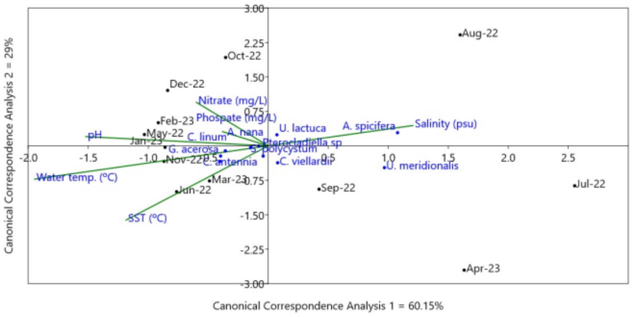

Figure 10. The effect of water quality on macroalgae IVI based on Correspondence Components Analysis (CCA) at Trenggole

The important value index (IVI) of seaweed in the intertidal zone of Trenggole is represented by the ten species with the most critical roles, including *Chaetomorpha* spp., *Ulva* spp., *Sargassum* spp., *Acrocytis nana*, *Gracilaria* spp., *Laurencia* spp., and *Pterocladiella* sp. According to the triplot graph, water temperature had the most substantial influence on the IVI of macroalgae in Trenggole during the study period, while phosphate had the weakest influence. This is likely due to fluctuating water temperatures, particularly between November 2022 and January 2023. Temperature is known to significantly affect macroalgae's survival, morphological forms, and reproductive cycles (Adharini *et al.* 2016). Additionally, temperature, irradiance, and photoperiod influence the growth rate of macroalgae thalli (Toth *et al.* 2020; Adharini and Kim, 2016).

Meanwhile, phosphate levels remained relatively stable in tropical areas, unlike in temperate regions where increased nutrients often result in higher macroalgae abundance (Kokabi *et al.* 2016). The cumulative eigenvalue represented by axes 1 and 2 in the triplot is 89.15%, indicating that 89.15% of the variation in the IVI of the seaweed community in Trenggole is explained by the six water quality parameters.

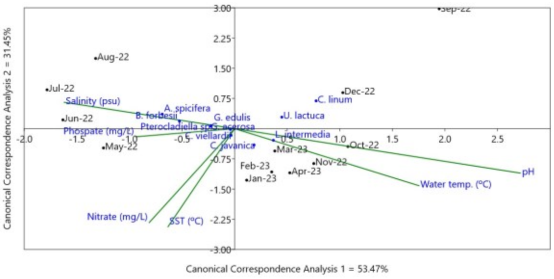

Figure 11. The effect of water quality on macroalgae IVI based on Correspondence Components Analysis (CCA) at Nguyahan

The macroalgae species with the most critical roles (highest IVI) at Nguyahan are represented by the ten most dominant species, including *Boergensenia forbesii*, *Chaetomorpha* spp., *Ulva* spp., *Acanthophora* sp., *Gracillaria* spp., *Laurencia* spp., and *Pterocladiella* sp. According to the triplot graph, pH is the parameter that strongly influences the important value index of seaweed in Nguyahan during the study, followed by temperature and salinity. In contrast, phosphate has the weakest influence, likely due to its relatively stable levels compared to the more fluctuating pH changes, particularly from July 2022 to October 2022. Similar results were observed on the eastern coast of Qeshm Island, Iran, where pH significantly affected macroalgae communities (Kokabi *et al.* 2016). Seasonal changes contribute to pH fluctuations, with lower pH levels correlating with reduced benthic community diversity (Baggini *et al.* 2014). The eigenvalue of the triplot, represented by axes 1 and 2, is 84.92. This indicates that 84.92% of the variation in the IVI of the macroalgae community at Nguyahan Beach can be explained by the six water quality parameters.

4. Conclusion

Seasonal changes and environmental conditions significantly influence the community structure of macroalgae. On the South Coast of Yogyakarta, Indonesia, the abundance and diversity of macroalgae increase during the transition of rainy season until beginning of the dry season. The areas 20 to 30 meters from the shoreline exhibit the highest abundance and coverage of macroalgae. Among the environmental factors, seawater temperature, pH, and salinity have the most substantial impact on macroalgae community structure. Rhodophyceae species constitute the largest component of the macroalgae communities in this region.

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