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Distribution Pattern of *Sargassum* spp. on the South Coast of Gunungkidul Regency, Special Region of Yogyakarta, Indonesia Using Satellite Imagery

Aniek Prasetyaningsih[1, 2*], Laurentius Hartanto Nugroho[3], Elizabeth Betty Elok Kristiani[2], Suryani Hutomo[4], Gatot Sasongko[5]

[1]Development Studies Doctoral Program, Faculty of Interdisciplinary, Universitas Kristen Satya Wacana, Salatiga 50711, Indonesia
[2]Departemen of Biology, Faculty of Biotechnology, Universitas Kristen Duta Wacana Yogyakarta, Yogyakarta 55224, Indonesia
[3]Departement of Tropical Biology, Faculty of Biology, Universitas Gadjah Mada Yogyakarta, Yogyakarta 55281, Indonesia
[4]Faculty of Biology, Universitas Kristen Satya Wacana, Salatiga 50711, Indonesia
[5]Interdisciplinary Faculty, Universitas Kristen Satya Wacana, Salatiga, Indonesia, Salatiga 50711, Indonesia

[*]Corresponding Author: aniek@staff.ukdw.ac.id

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ABSTRACT

Sargassum spp. is one of the most abundant types of macroalgae on Gunungkidul coast, Yogyakarta, Indonesia. Its ability to adapt to the characteristics of the Gunungkidul coast causes this macroalgae to thrive. The highly varied biochemical composition of this macroalga species makes it a promising natural resource. However, efforts to develop it optimally have not been made until now. Therefore, an initial study is needed to determine the distribution pattern of Sargassum in the waters of Gunungkidul for sustainable management. The present study utilized secondary data acquired from BMKG and Satellite Imagery (Sentinel-2 L2A). Measurements of normalized difference vegetative index (NDVI), *Sargassum* index (SI), and sea surface temperature (SST) were collected over three years (2020-2022) using the ESA SNAP and QGis software. The classification of the Sargassum area was carried out using Random forest. Data analysis used univariate and Posthoc Tukey with a 95% confidence level and bivariate correlation between environmental parameters and vegetation index and area. Satellite imagery data indicated that *Sargassum* is present year-round in Gunungkidul waters. The average results of humidity and SST in Gunungkidul waters during 2020-2022 significantly affect the growth of Sargassum. The largest *Sargassum* growth area was found in January-May and August-October at Ngunggah Beach and its surroundings, the Central part, namely Ngrenehan Beach, Kukup, Sepanjang, Watu Kodok, Drini, Betueng, Krakal, Sadranan, Trenggole, and Dadapan Beach. The mean Sargassum biomass in Gunungkidul waters exhibited a greater wet weight in comparison with other regions in Indonesia and Asia, particularly during the months of January-April and September-November.

INTRODUCTION

Sargassum spp. is a macroalgae from the class Phaeophyceae, order Fucales, family Sargassaceae, and genus *Sargassum* C. Agardh, 1820 **(GBIF, 2024)**. *Sargassum* is found in the Atlantic, Pacific, and Indian Oceans and in temperate, subtropical, tropical, and

Alaska regions. This particular variety of seaweed, known as golden seaweed, is characterized by its carpet-like golden brown expanse when it floats in the ocean **(Butler *et al.*, 1983; Stoner, 1983; Kadi, 2005; Guiry & Guiry, 2018; Low *et al.*, 2019a; Fidai *et al.*, 2020; Yip *et al.*, 2020a; Davis *et al.*, 2021**). A comprehensive review of over than a 100 research articles published between 2005 and 2022 revealed that *Sargassum* is distributed universally over the continent. The widest distribution and most significant number of species are found in the East, Southeast, and Southwest Asia **(Butler, *et al.*, 1983; Stoner, 1983; Kadi, 2005; Low *et al.*, 2019; Fidai *et al.*, 2020; Yip *et al.*, 2020; Guiry & Guiry, 2022)**.

The aforementioned number and distribution require additional investigation. They may not sufficiently represent the diversity of current species due to the presence of numerous species validations relying on morphogenetic traits that introduce bias in identification outcomes. This macroalga exhibits remarkable adaptability, enabling it to thrive in diverse aquatic environments, adhere to surfaces such as dead coral and coral reef material, or float in waters (pelagic). Globally, of the 148 *Sargassum* species that can be tracked, several species are cosmopolitan, namely the types *Sargassum duplicatum*, *S. swartzii* (Turner) C.A. Agardh, *S. polycystum*, and *S.ilicifolium*, different from the endemic types *S. brandegeei*, *S. herporhizum*, *S. horridum*, *S. sinicola* (America), *S. lapazeanum* (Mexico) *S. vestitum*, *S. vigorosum*, *S. fallax*, *S. novae-hollandiae*, *S. lacerifolium*, *S. scabridum*, *S. schnetteri* (Australia), and *S. latif olium* (Africa) **(Guiry & Guiry, 2022)**. This difference is greatly influenced by the physiological conditions of each *Sargassum* species, which can survive in specific environmental conditions **(Shin *et al.*, 2014; Arellano-Verdejo & Lazcano-Hernández, 2021; Kwan *et al.*, 2022; Prasetyo & Simanjuntak, 2022; Schamberger *et al.*, 2022; Stankovic *et al.*, 2022)**.

Microclimate refers to the precise climatic conditions in a limited geographical region, either below or on the Earth's surface, within a canopy or vegetation in a terrestrial environment, glaciers, or oceans. These conditions have a significant impact on ecological processes such as decomposition, nutrient cycling, succession, and productivity of living organisms **(Chen *et al.*, 1999)**. The morphological and growth variety of *Sargassum* is directly affected by spatio-temporal fluctuations, climate, and seasons, which exert pressure on the survival of macroalgae and necessitate the adaptation process. Changes in the distribution, morphology, and synthesis of secondary and primary metabolites demonstrate the process of adaptation, which ensures survival, growth, and development. The large-scale distribution of *Sargassum* is influenced by surface currents, winds, and spatiotemporal fluctuations in growth and mortality **(Canciyal *et al.*, 2014; Bhavika *et al.*, 2021; Sumandiarsa *et al.*, 2021)**. This spatial and temporal variation greatly affects the variety of macroalgae assemblages in the waters of western Indonesia **(Sumandiarsa *et al.*, 2021)**.

Sargassum spp. in Indonesia thrives on diverse rocky beaches in both intertidal and tidal zones, where it is anchored to rocks or coral to prevent being swept away by the coastal currents (benthic). *Sargassum* habitat can be found on practically every island, including the Riau Islands, the South Coast of Java, Bangka Belitung, West and East Nusa Tenggara, Bali, Sulawesi, and Maluku **(Verheij & Prud'homme van Reine, 1991; Kadi, 2005; Sukiman *et al.*, 2014)**. According to reference evaluations, there are 56 species of *Sargassum* spp. in Indonesia, with the most diversity found on Yogyakarta's Gunungkidul coast, which has up to 17 (30.35%) species **(Kadi, 2005; Triastrinurmiatiningsih *et al.*, 2011; Indrani & Budianto, 2013; Marianingsih *et al.*, 2013; Nurmiyati, 2013; Pratama *et al.*, 2015; Prasetyaningsih & Rahardjo, 2016; Suryandari, 2017; Titlyanov *et al.*, 2017; Widyartini *et al.*, 2017; Manteu *et al.*, 2018; Rahardjo & Prasetyaningsih, 2018; Khasanah *et al.*, 2019; Aziz & Chasani, 2020; Ramzi & Adharini, 2020; Sodiq & Arisandi, 2020; Dwi *et al.*, 2021; Ningrum & Chasani, 2021; Nurhidajah *et al.*, 2024)**.

Gunungkidul Regency is one of the regencies in the Special Region of Yogyakarta Province, consisting of 18 sub-districts and 144 villages/sub-districts, with Wonosari serving as its capital. Factual data show that there are 136 beaches in Gunungkidul, with 76 beaches that are seaweed habitats **(Gunungkidul, 2022)**. Gunungkidul Regency has an area of 1,485km^2, or approximately 46% of the total area of the province, and a coastline of 71km (62.83% of the length of the DIY coast), which directly faces the Indian Ocean (http://bappeda.jogjaprov.go.id/dataku).

Sargassum spp., highly prevalent macroalgae on the South Coast, have not been fully utilized for their significant potential in processing into derivative products and food, as well as for exporting as dry material. The available database on the distribution and biomass of this macroalga is still very insufficient and lacks comprehensive documentation. However, these data serve as a crucial foundation for formulating policies and development strategies, given that the harvest of this macroalgal still depends on nature. In an effort to explore and monitor its existence and productivity, remote sensing tools (satellite imagery) are needed, which are expected to facilitate observation **(Shin *et al.*, 2014; Arellano-Verdejo & Lazcano-Hernández, 2021; Kwan *et al.*, 2022; Prasetyo & Simanjuntak, 2022; Schamberger *et al.*, 2022; Stankovic *et al.*, 2022)**. The use of satellite imagery in this study is crucial due to the large research area, which is difficult to access because of steep cliffs, high waves, and the presence of various types of macroalgae growing in the same location. Satellite imagery also allows for the accurate distinction between populations of seaweed such as *Ulva*, *Sargassum*, and other species in the waters through spectral differences **(Hossain *et al.*, 2015; Setyawidati *et al.*, 2018; Bermejo *et al.*, 2020; Mora-Soto *et al.*, 2020)**. Therefore, in this study, satellite imagery was used as a tool to effectively and accurately observe the growth patterns of *Sargassum*.

To investigate the application of bioprospecting in Gunungkidul, a study was undertaken to examine the distribution of *Sargassum* spp. on the Gunungkidul coast. This study was based on the vegetation index obtained from satellite imagery data, and the impact of microclimate on *Sargassum* growth was evaluated. This study aimed to compile a comprehensive database on the distribution, biomass, and microclimate parameters that impact *Sargassum* on the Gunungkidul coast. This will enable the analysis and optimization of sustainable management strategies for *Sargassum* on the Gunungkidul Coast.

MATERIALS AND METHODS

1. Research sites

This research was conducted along the South Coast, Gunungkidul Regency, in the Special Region of Yogyakarta (DIY) Province. It is geographically located in coordinates 7°46′ LS-8°09′ LS dan 110°21′ BT-110°50′ BT. Gunungkidul has an area of 1,485km^2 with a coastline of 71km or 62.83% of the total length of the coast in DIY (http://bappeda.jogjaprov.go.id/dataku). Satellite imagery data were taken from the entire length of the Gunungkidul coast (Fig. 1). A biomass sampling was carried out regarding ten beaches, specifically Mesra, Kukup, Porok, Sepanjang, Watukodok, Drini, Krakal, Sadranan, Trenggole, and Watulawang in October - November 2022.

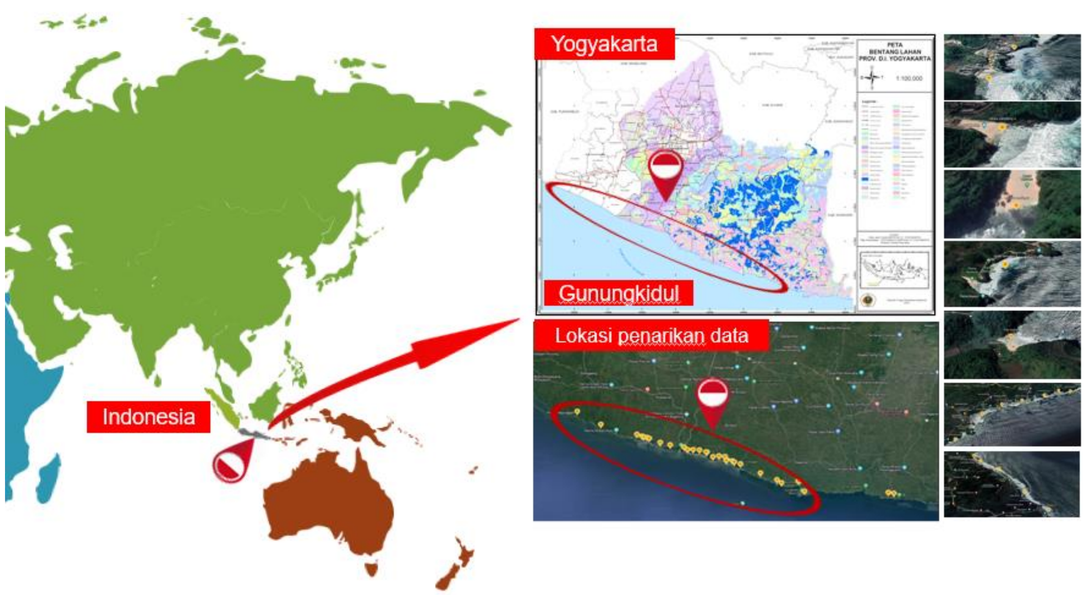


Fig. 1. Overview of *Sargassum* spp. distribution research locations

2. Satelite imagery

This study used quantitative and qualitative approaches with explorative methods. Several software applications were used: ESA SNAP QGIS, microsoft excel, Sentinel 2 L2A imagery (https://scihub.copernicus.eu/), machine learning, and ordinary kriging programs. The parameters assessed consist of calculating the vegetation index (SI:

Sargassum index), NDVI (Normalized difference vegetation index), chlorophyll c, fucoxanthin, and the extent of *Sargassum* distribution. Oceanic surface temperature (SST) and total suspended solid (TSS) were quantified using the Sentinel 3 SLSTR satellite from MODIS (Fig. 2).

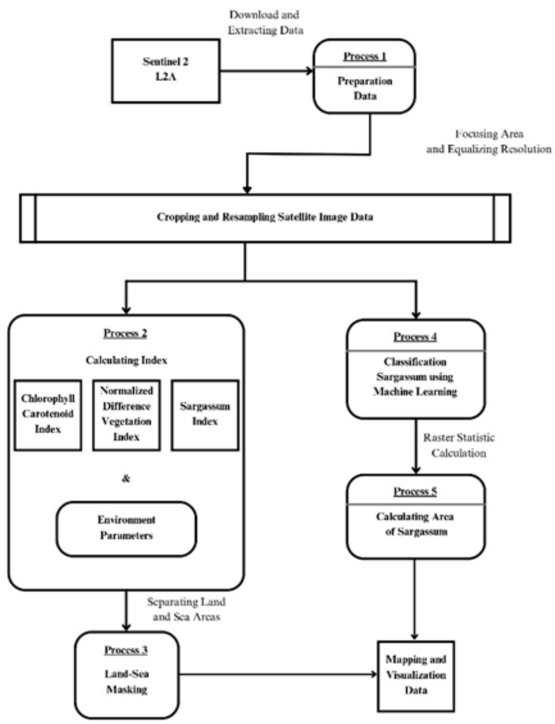


Fig. 2. Stages of data retrieval vegetation index calculation and environmental parameters using satellite imagery

Process 1: Data preparation

Sentinel 2 L2A provided satellite imagery consisting of 12 bands with varying resolutions and wavelengths. The bands, which had wavelengths ranging from 0.443 to 2.190 micrometers, were cropped to fit the research area and resampled to ensure uniform resolution across all bands.

Process 2: Calculating vegetation indices

In this stage, various numerical data indices were calculated, including the normalized difference vegetation index (NDVI), the *Sargassum* index (SI), and environmental parameters such as total suspended solids (TSS) and sea surface temperature (SST).

Process 3: Land-sea masking

During this stage, ESA-SNAP was used to segregate land and sea regions, allowing for measurements to focus specifically on marine areas.

Process 4: Ordinary kriging

In the ordinary kriging stage, interpolation was performed at 40 sample points, which included coastal locations along the west-east axis and points in the sea. This step aimed to predict values in locations where data were unavailable, extending beyond the sample points.

Process 5: Sargassum classification

Sargassum classification was conducted using machine learning techniques. Areas were categorized based on pixel analysis to determine their respective types. The classification employed the random forest method, which utilized previously marked *Sargassum* objects to automate the grouping based on pixel characteristics.

Process 6: Calculating sargassum area

In this classification stage, the random forest approach was applied to determine area measurements in square meters based on region type. The area of *Sargassum* growth was derived from these classification results **(Xiao *et al*., 2022)**. The final outcomes of each process are presented in graphs and maps.

3. Normalized differences vegetation index (NDVI)

Normalized difference vegetative index (NDVI) was used to identify vegetation cover in an area, including waters. NDVI values >0 reflect the presence of vegetation cover. High vegetation cover is in the range of 0.1 to 0.6. The higher the NDVI value, the higher the green cover **(Dierssen *et al.*, 2015)**. The NDVI value was calculated using Eq. 1 (**Campbell & Wynne, 2011; Siddiqui *et al.*, 2019**):

$$Normalized\ Differences\ Vegetation\ Index = \frac{NIR - Red}{NIR + Red} \quad (1)$$

4. *Sargassum* index (SI)

The *Sargassum* index (SI) is a measure of reflectance at 650 and 630nm used to differentiate *Sargassum* from seagrass algae and other floating plants lacking the 630nm absorption characteristic **(Dierssen *et al.*, 2015; Shin *et al.*, 2021)**. Hence, this value can indicate the presence of *Sargassum* in the research location. When visualizing the interpolation results of satellite image data, a value greater than 1 indicates *Sargassum*, whereas a value less than 1 indicates seagrass debris. The result of Eq. 2 was used to calculate the SI value using Eq. 3.

$$R_{hoC,\lambda} = \frac{\pi L^{Corr}_{TOA,\lambda}}{F_{0\lambda} \cos\theta_s} - R_{r\lambda} \quad 2)$$

$$Sargasssum\ Index = \frac{R_{hoC,650\ nm}}{R_{hoC,630\ nm}} \quad 3)$$

5. Total suspended solid

Total suspended solid (TSS) is a suspended material of mud and microorganisms from soil erosion or erosion carried into water or nutrients. Water with a higher TSS value will exhibit greater turbidity. Consequently, the hindrance of sunlight penetration into the water might lead to the disruption of photosynthesis, thus affecting the reduction of dissolved oxygen levels **(Riadi *et al.*, 2022)**. TSS was calculated using Eq. 4.

$$Total\ Suspended\ Solid = 2950\ x\ Vegetation\ Red\ Edge\ x\ 1.357 \quad (4)$$

(https://www.atlantis-press.com/article/125981466.pdf)

6. Sea surface temperature (SST)

SST is used as an indicator of the amount of water vapor in the atmosphere and plays a role in cloud formation over Indonesia's territory, which results in a decrease or increase in temperature above sea level. This data was sourced from the SST data available at https://iridl.ldeo.columbia.edu/maproom/Global/Ocean_Temp/index.html.

7. Humidity, lighting duration, rainfall, and wind speed

Environmental parameters of humidity, lighting duration, rainfall, and wind speed were secondary data obtained from BMKG Mlati-Sleman Yogyakarta.

8. Quantification of macroalgae biomass

The biomass amount was predicted by sampling in ten locations, namely by conducting triplicate sampling on a 1x1m^2 plot and weighing the wet weight of *Sargassum* in each area. The mass of *Sargassum* biomass was determined by multiplying the expected growth area by the wet weight (kg) per square meter (m^2) **(Mizuno *et al.*, 2014; Wang & Hu, 2016, 2018)**.

9. Data analysis

The significance of environmental parameter variations in each period was tested using ANOVA (Analysis of variance) followed by Post Hoc tests, namely the Scheffe test and Tukey test, at a 95% confidence level. The relationship between environmental factors per year with NDVI and SI values and the area of growth was analyzed using a bivariate correlation coefficient with significance at a 95% confidence level. All analyses were performed using SPSS version 25.0.

RESULTS

1. Microclimate on the Gunungkidul coast

The climatic conditions in Gunungkidul are characterized by a wet season from October to April and a dry season from May to September **(Gunungkidul Regency**

Government, 2022). Environmental conditions from BMKG secondary data show fluctuations throughout 2020-2022 (Table 1). Significant fluctuations are observed primarily in May-September, with October-April demonstrating statistical significance at a 95% confidence level (*P*<0.05). The period from May to September is characterized by cooler temperatures, little rainfall, and low total suspended solids (TSS) but high humidity, and vice versa.

Table 1. Average environmental conditions along the Gunungkidul coast in 2020-2022

Environment data	**Month**	**Year**		
		2020	**2021**	**2022**
		mean ± SD	**mean ± SD**	**mean ± SD**
Humidity (%)	Jan-Feb	87 ± 2.074[a]	90 ± 2.51[b]	87 ± 3.209[b]
	Mar-Apr	92 ± 2.074[c]	92 ± 2.51[b]	92 ± 3.209[d]
	May-Jul	89 ± 2.074[b]	87 ± 2.51[a]	85 ± 3.209[a]
	Aug-Sep	90 ± 2.074[b]	87 ± 2.51[a]	84 ± 3.209[a]
	Oct-Dec	87 ± 2.074[a]	86 ± 2.51[a]	89 ± 3.209[c]
SST (°C)	Jan-Feb	30.33 ± 1.747[c]	28.67 ± 1.478[b]	28.67 ± 0.702[a]
	Mar-Apr	29.33 ± 1.747[b,c]	28.83 ± 1.478[b]	29 ± 0.702[a]
	May-Jul	27.17 ± 1.747[a,b]	27 ± 1.478[a,b]	28.33 ± 0.702[a]
	Aug-Sep	26 ± 1.747[a]	25.5 ± 1.478[a]	27.17 ± 0.702[a]
	Oct-Dec	29 ± 1.747[b,c]	29 ± 1.478[b]	28 ± 0.702[a]
Lighting duration (h/d)	Jan-Feb	5.7 ± 1.473[c]	9.5 ± 1.053[a]	9.5 ± 0.973[b]
	Mar-Apr	4,7 ± 1.473[b]	9.8 ± 1.053[a]	8.71 ± 0.973[b]
	May-Jul	7.45 ± 1473[d]	7.2 ± 1.053[a]	7.2 ± 0.973[a]
	Aug-Sep	7.5 ± 1.473[d]	8.2 ± 1.053[a]	9.5 ± 0.973[b]
	Oct-Dec	4.4 ± 1.473[a]	9 ± 1.053[a]	9.3 ± 0.973[b]
Wind speed (m/s)	Jan-Feb	1.8 ± 0.040[a,b]	3 ± 2.491[a]	3 ± 0.447[a]
	Mar-Apr	1.5 ± .,40[a]	3.17 ± 2.491[a]	3 ± 0.447[a]
	May-Jul	2.14 ± 0.40[b]	4 ± 2.491[a]	3 ± 0.447[a]
	Aug-Sep	2.5 ± 0.40[b]	3.9 ± 2.491[a]	4 ± 0.447[a]
	Oct-Dec	2.3 ± 0.40[b]	9 ± 2.491[b]	3 ± 0.447[a]
TSS (mg/L)	Jan-Feb	952.19 ± 358.46[e]	234.5 ± 760.14[c]	3.93 ± 461.73[a]
	Mar-Apr	99.74 ± 358.46[b]	99.74 ± 760.14[b]	450.67 ± 461.73[c]
	May-Jul	91 ± 358.46[a]	93.13 ± 760.14[a]	23.92 ± 461.73[b]
	Aug-Sep	228 ± 358.46[c]	476.12 ± 760.14[d]	23.92 ± 461.73[d]
	Oct-Dec	248.51 ± 358.46[d]	189.84 ± 760.14[e]	1068.75 ± 461.73[e]
Rainfall (mm/d)	Jan-Feb	125 ± 128.86[a,b]	350 ± 135.49[b]	63 ± 41.916[a,b]
	Mar-Apr	125 ± 128.86[b]	275 ± 135.49[c]	125 ± 41.916[b]
	May-Jul	35 ± 128.86[a]	35 ± 135.49[a]	35 ± 41.916[a]
	Aug-Sep	35 ± 128.86[a]	75 ± 135.49[a]	15.5 ± 41.916[a]
	Oct-Dec	350 ± 128.86[c]	250 ± 135.49[b]	75 ± 41.916[a,b]

SST: Sea Surface temperature; TSS: Total Suspended Solid. Different notations indicate significant differences at the 95% confidence level.

2. The growth area of *Sargassum* spp. in Gunungkidul waters

Data on the area of *Sargassum* growth throughout 2020-2022 showed fluctuations (Fig. 3) and unpredictable patterns. The largest distribution area was found in September 2020 (22,713.50km^2), March 2021, and March 2022 (26,180.30 and 24,024.40km^2).

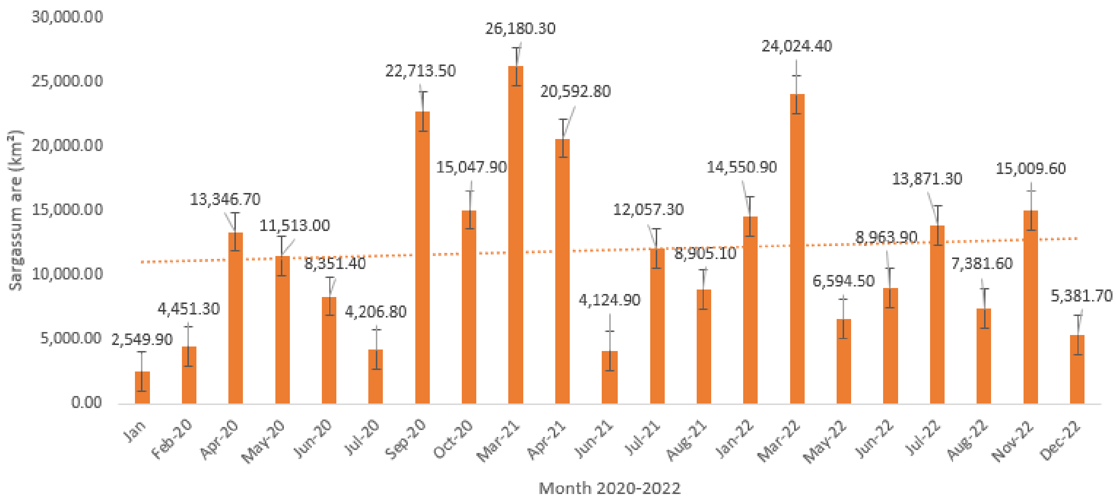


Fig. 3. *Sargassum* spp. growth area graph for the years 2020-2022. The region of 0 denotes the absence of data in satellite imagery

3. Normalized difference vegetation index (NDVI) and *Sargassum* index (SI)

The results of NDVI and SI interpolation at 40 sample points (Fig. 4) show the presence of vegetation cover along the coast, especially the central Gunungkidul coast. NDVI interpolation in April, June, August, and December showed vegetation covering the coastline (NDVI>0) with a value of 0.001-0.568 (Fig. 5).

In June 2020-2023, the NDVI value of 0.101-0.568 indicates vegetation cover. In April, August, and December, it was only identified in several locations. The coastal locations with the highest vegetation are Ngunggah and Drini.

The SI value >1 indicates the presence of *Sargassum* clustered in the west (Ngunggah Beach and its surroundings) and also in the Central part consisting of Ngrenehan Beach, Kukup, Sepanjang, Watu Kodok, Drini, Krakal, Betueng, Sadranan and extending to Trenggole and its surroundings. At the same time, in the East, it was found at Dadapan Beach (Fig. 6).

(a) (b)

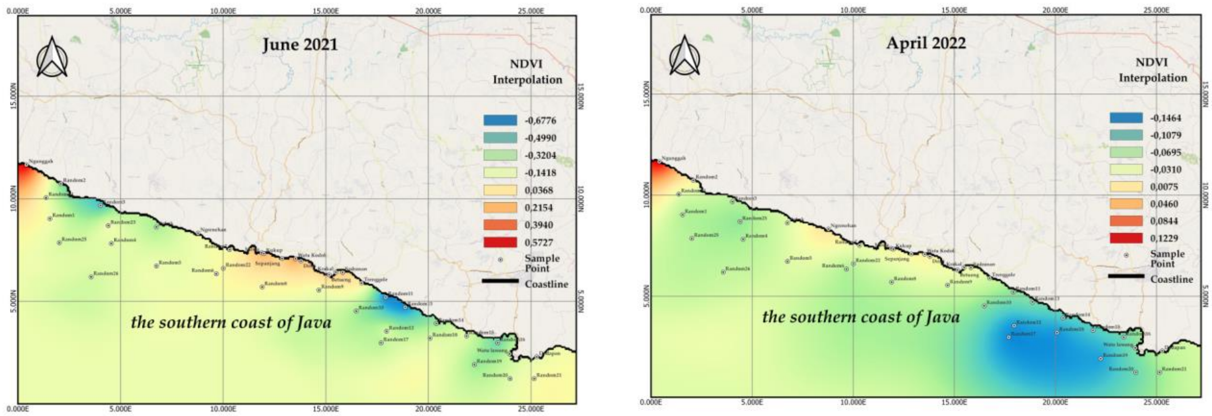


Fig. 4. NDVI Interpolation Mapping in Gunungkidul Beach. (a) June 2021 (b) April 2022. The color gradation shows the NDVI value. Blue (<0) indicates no vegetation cover, and red (>0) indicates vegetation cover

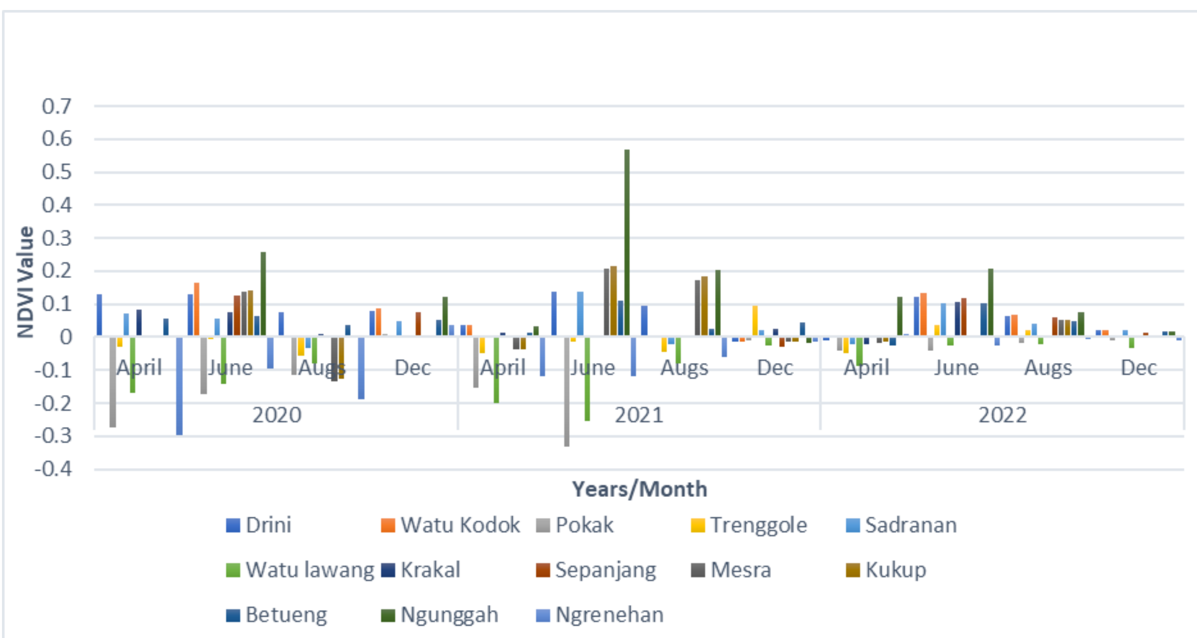


Fig. 5. NDVI values in April, June, August and December in 2020-2022 at ten Gunungkidul beaches location

The presence of *Sargassum* was identified based on the SI (*Sargassum* index) interpolation value. The distribution of *Sargassum* was observed in the intertidal zone of Gunungkidul waters. Forty random sampling locations were determined to represent the East to West and in the ocean (Fig. 6).

(a) (b)

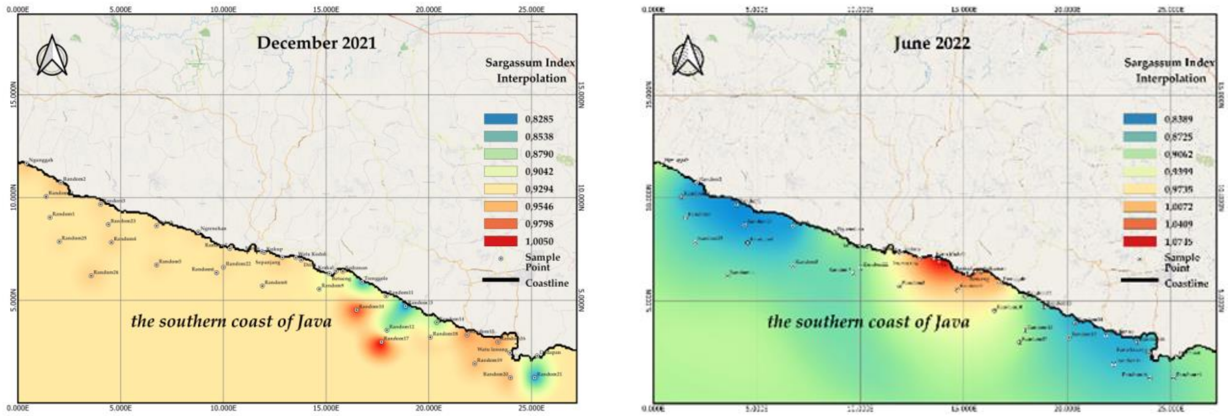


Fig. 6. SI Interpolation mapping on Gunungkidul Beach in 2020-2022. Map of SI interpolation values in (a) April 2020, (b) June 2022, (c) August 2021, and (d) December 2020-2021. *Sargassum* was indicated if the SI value is >1. Light blue to blue colors indicate seagrass debris, and orange to red colors indicate the presence of *Sargassum*

SI interpolation shows that *Sargassum* can be found throughout time, although only debris or fragments of *Sargassum thallus* (SI <1) were detected. *Sargassum* generally grows with a broader distribution in April and June compared to other months, while in August, the broadest distribution was only found in 2021. The results of this SI interpolation show that in 2020 and 2022, the *Sargassum* distribution was higher than in 2022 (Fig. 7).

4. Confirmation of the presence of *Sargassum* spp., chlorophyll c, and fucoxanthin

Confirmation of the presence of *Sargassum* was carried out through reflectance, which identified the presence of fucoxanthin and chlorophyll c. This was done to ensure the presence of *Sargassum* in the location marked in Random Forest as the *Sargassum* species. The findings from the monitoring of chlorophyll c and fucoxanthin at Ngunggah Beach in November 2022 revealed that chlorophyll c was detected at an absorption wavelength of approximately 632nm, while fucoxanthin was detected at a wavelength ranging from 480 to 520nm (Fig. 8a, b).

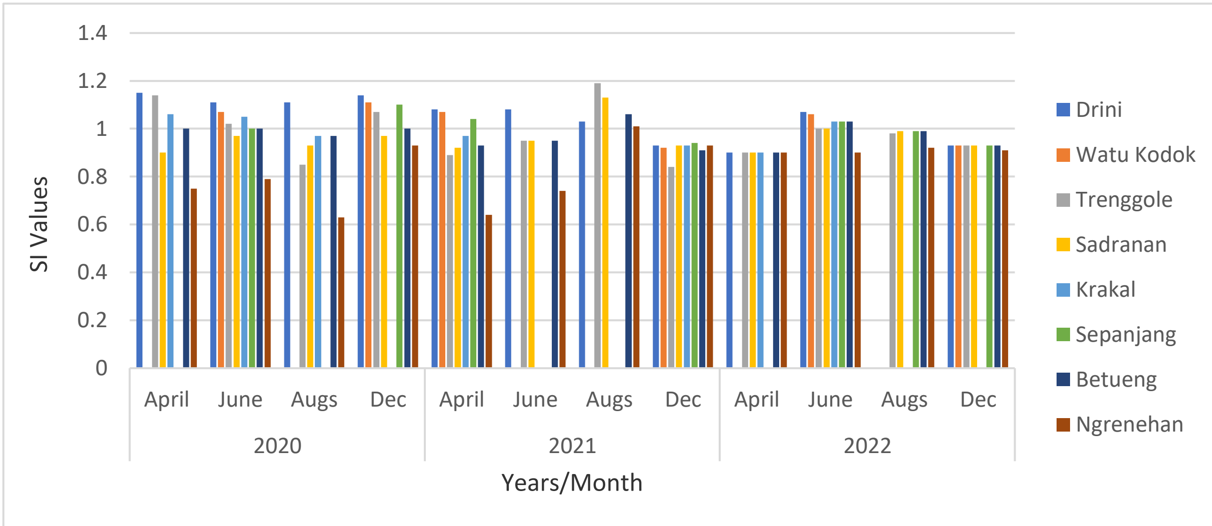
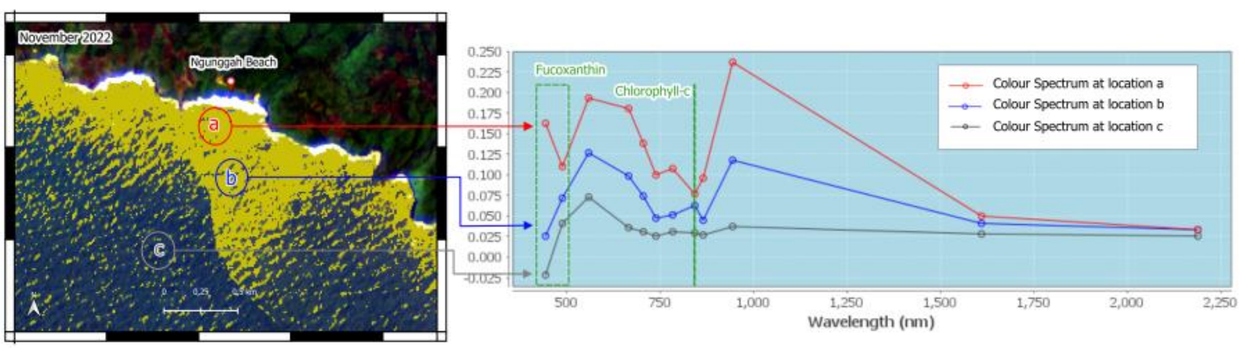


Fig. 7. SI values in April, June, August and December in 2020-2022 at ten Gunungkidul beaches

(a)



(b)

Fig. 8. Confirmation of the presence of *Sargassum* spp. (a) Chlorophyll c and fucoxanthin in the spectra 480-520 and 480-635nm (b) Ngunggah Beach, the red arrow shows the *Sargassum* colony

5. The influence of environmental factors on the growth area and vegetation index of *Sargassum*

The environmental data (SST, humidity, rainfall, and wind direction) for the period 2020-2022 for the period 2020-2022 exhibited unpredictable variations. The regression correlation analysis at a 95% significance level revealed that humidity was the only factor with a statistically significant negative impact on SI (Table 2). This implies that high humidity leads to a drop in the SI value, whereas low humidity increases the SI value.

Table 2. Correlation of environmental factors with interpolation of vegetation index and growth area

Environment parameter	SI		NDVI		Luas area (km^2)	
	sig	r	sig	r	sig	r
Humidity (%)	0,047*	-0,997*	0,141	-0,975	0,495	-0,712
SST (°C)	0,832	0,260	0,738	0,401	0,384	0,824
Lighting duration (h/d)	0,501	0,706	0,596	0,593	0,950	0,079
Wind speed (m/s)	0,955	0,070	0,950	0,079	0,596	-0,593
TSS (mg/L)	0,884	0,181	0,979	0,032	0,667	-0,500
Rainfall (mm/day)	0,747	-0,387	0,652	-0,520	0,298	-0,893

Note: * Pearson correlation. Correlation is significant at the 0.05 level (2-tailed). SI: *Sargassum* index; NDVI: Normalized difference vegetation index; SST: Sea surface temperature; TSS: Total suspended solid.

Other regression correlation results did not show any significant relationship, but SI and NDVI are positively correlated with SST, lighting duration, wind speed, and TSS. A reasonably strong correlation appeared between SST and lighting duration with NDVI (r = 0.401 and 0.593) and SI with lighting duration (r = 0.706). In contrast to other parameters, the area is negatively correlated with humidity, TSS, and rainfall. Based on the strong correlation, high temperatures and long lighting duration are essential in supporting increased *Sargassum* growth.

6. Biomassa

The biomass at ten sampling sites, with an average wet weight of 11.96±1.83kg/ m^2, had a small range of variation (9.67 – 15.83kg/ m^2). Total biomass was calculated based on the multiplication of the *Sargassum* area's average biomass by the average *Sargassum* biomass per kg/m^2. Hence, the variation in *Sargassum* biomass on Gunungkidul beach exhibited a similar trend to the variation in the area pattern. The highest total biomass amounts in 2020 were recorded in April (159,626.53 tons), September (179,972.88 tons), and October (271,653.46 tons). The peak total biomass in 2021 was recorded in March-April, ranging from 313,116.39 to 246,289.89 tons. In 2022, the biomass exceeded 287,331.82 tons in March and 179,514.82 tons in November (Table 3).

Table 3. Prediction of *Sargassum* spp. biomass based on area

Month	Biomass (ton)	Month	Biomass (ton)	Month	Biomass (ton)
Jan-20	30,496.80	Mar-21	313,116.39	Jan-22	174,028.76
Feb-20	53,237.55	Apr-21	246,289.89	Mar-22	287,331.82
Apr-20	159,626.53	Jun-21	49,333.80	May-22	78,870.22
May-20	137,695.48	Jul-21	144,205.31	Jun-22	107,208.24
Jun-20	99,882.74	Aug-21	106,505.00	Jul-22	165,900.75
Jul-20	50,313.33	nd	nd	Aug-22	88,283.94
Sep-20	271,653.46	nd	nd	Nov-22	179,514.82
Oct-20	179,972.88	nd	nd	Dec-22	64,365.13

Biomass prediction: The area of Sargassum cover (per 1x1m) had an average wet weight of 11.96±1.90kg.
nd : not detected

DISCUSSION

1. Topography and microclimate of Gunungkidul waters

The Gunungkidul Regency is situated in the Southeast region of the Special Region of Yogyakarta. It is geographically located in coordinates 7°46′ LS-8°09′ LS and 110°21′ BT-110°50′ BT. Gunungkidul Regency contains a total area of 1,475.13km^2, including a coastline of 71km^2 (Fig. 1). Adjacent to the Indian Ocean, Gunungkidul Regency has a coastal geostrategy characterized by 28 small coral islands that serve as homes for diverse marine biota. The Gunungkidul coast currently has 136 beaches, 76 of which are seaweed habitats. One of the characteristics of the South Coast is the high rolling waves (swell) due to the influence of the Indian Ocean **(LIPI, 2015; IOC, 2020)**. The extreme high waves in October-December are the biggest obstacle that causes the suboptimal development of marine fisheries including seaweed **(Pemerintah daerah Gunungkidul, 2023)**. Statistical data from 2020-2022 indicate varying monthly microclimate conditions (Table 1) and notable variations in the length of daylight, wind speed, and TSS. However, the conditions of SST, duration of sunlight, TSS, and rainfall still meet the range of requirements for *Sargassum* growth, allowing it to be found in some regions practically every month of the year.

2. Area of *Sargassum* spp. growth

Sargassum spp., *Ulva* sp., and *Gracilaria* sp. are the most frequent macroalgae in Gunungkidul's waters. *Sargassum* in Gunungkidul is benthic in the intertidal area. The thallus is attached to the coral, providing a holdfast, and has bubbles (vesicles) used as air pockets to float. *Sargassum*'s benthic nature causes it to be below the sea surface when it grows in deep seas or during high tide (Fig. 8b). This species differs from the holopelagic *Sargassum* found in the Equatorial Atlantic, which remains floating in the seas for its whole lifespan **(Schell *et al.*, 2015; Brooks *et al.*, 2018, 2019; Desrocher *et al.*, 2022; Alleyne *et al.*, 2023)**. The area of *Sargassum* fluctuates, with the broadest values occurring in March-May and September-November. However, the dynamics of changes in the area occur throughout the year and are challenging to assess due to the limited availability of satellite imagery data. The findings of this study do not entirely align with previous research conducted on European beaches on *S. horneri* and *S. fusiform*. The previous study by **Arenas and Fernández (2000)** reported that the growth phase of *Sargassum* extends from August to November but decelerates from February to April. The vast expanse of *Sargassum* is due to environmental conditions that facilitate its growth during that month, including warm temperatures, highlighting duration, and low rainfall. These findings do not entirely align with information from seaweed pickers who state that *Sargassum* grows only in September-November. The disparity arises from the fact that pickers can only observe *Sargassum* when it is thickly grown for harvest, yet it remains invisible or overlooked when it is in the form of seeds or during the growth phase.

3. Sargassum vegetation index: NDVI (Normalized difference vegetation index) and SI (*Sargassum* index)

Interpolation of NDVI values was taken at ten coastal points and 30 random points in the deep ocean representing the East to West. In observations from April to December, vegetation cover was found, but the vegetation type could not be identified. The results of interpolating NDVI values to ten points ranged from 0.005 to 0.568 (Fig. 4). In June 2020-2022, the average NDVI value was >0.1, indicating vegetation cover in most sampling locations (Fig. 5).

Sargassum in the waters was identified by analyzing the SI interpolation value. A SI value greater than 1 indicates the existence of the *Sargassum* habitat. The interpolation results show that the location of the *Sargassum* habitat is consistently found in the West, mainly in the Central part and the East. *Sargassum* growth in the West is located mainly at Ngunggah Beach and its surroundings. At the same time, the Central Gunungkidul coast is found at Ngrenehan, Kukup, Sepanjang, Watu Kodok, Drini, Betueng, Krakal, Sadranan, and Trenggole beaches and their surroundings. In the East, it is found around Dadapan Beach (Fig. 5). These locations are waters that form a symbiont ecosystem between coral reefs and marine biota. This symbiosis makes the location a fertile habitat for *Sargassum* and other macroalgae. Research has indicated that *Sargassum* is found on several beaches including Trenggole, Porok, Sepanjang, Drini, Sarangan, Krakal, and Wediombo **(Wandha *et al.*, 2014; Prasetyaningsih & Rahardjo, 2016; Suryandari, 2017; Aziz & Chasani, 2020; Sodiq & Arisandi, 2020; Ningrum & Chasani, 2021)**. Furthermore, the species' existence along the coastline was documented by **Kadi (2005)** and **Dwi *et al.* (2021)**. The presence of *Sargassum* at Dadapan Beach is also strengthened by the monitoring of the primary pigments of *Sargassum*, namely chlorophyll c and fucoxanthin in November 2022 at peak wavelengths of 460, 485, 632nm and 480-520nm (Fig. 8a) **(Beach *et al.*, 1997; Orzymski *et al.*, 1997; Johnsen & Sakshaug, 2007; Dawes, 2016; Sanger *et al.*, 2022)**. The presence of pigment chlorophyll c and fucoxanthin was also found in a research conducted on *S. polycytum* from the coast of Sumbawa, Indonesia **(Kusmita *et al.*, 2023)**.

Sargassum inhabits a coastal environment characterized by a substrate mainly composed of solid, large, steep, and rough sandy coral rocks. This is in accordance with Elias' statement that tropical coral reefs serve as the focal point of marine biodiversity, providing a habitat for thousands of species. These coral reefs are symbiotic in the aquatic ecosystem with flora (algae) and marine fauna (marine invertebrates in the phylum Cnidaria). Algae usually grow in shallow waters as a stable place to attach to life and are still exposed to sunlight for photosynthesizing **(Elias, 2015)**. Sargassum in Gunungkidul waters lives on dead or living coral. This organism exhibits growth from the lowest point of the sun's ebb to being immersed at the depth limit. It remains efficient for photosynthesis by holdfast to the substrate, sand, coral, dead coral fragments, or rocks. The coral rock serves as a crucial substrate for Sargassum by facilitating attachment through the formation of holdfast, a key mechanism for vegetative reproduction throughout the year. The results of other studies also report that *Sargassum* inhabits tropical and subtropical waters, spanning from the mid-littoral to sublittoral zones, on substrates such as rock, huge rocks, and hard coral rock in the open zone **(Kadi, 2005; Titlyanov *et al.*, 2017)**. *Sargassum* was not detected in areas where beaches with high cliffs and waves constantly hit the coral, preventing *Sargassum* from growing and developing properly. Direct observations in the field revealed that several locations where *Sargassum* was not identified had relatively low amounts of the seaweed, resulting in these areas being overlooked in satellite imagery. The limitations of satellite imaging include the restricted availability of recoverable data and the reflectance from the waterways, which can cause interference and reduce sensitivity in detecting *Sargassum*.

According to the analysis of SI, NDVI, growth area, field observations, and macroalgae production data from the Fisheries and Marine Service for 2020-2022, the development cycle pattern of *Sargassum* may be described as follows. *Sargassum thallus* development undergoes over January and February. The primary genesis of this thallus is believed to be the development of filamentous holdfast. Between March and May, thallus development arises from the residual holdfast and fragmentation of macroalgae that remain after harvest or occur spontaneously. During June and July, seedling regeneration occurs by vegetative and generative reproduction in areas with minimal human intervention. *Sargassum* seedlings reach maturity after rapid development in August-October; however, their thallus diminishes in November-December due to harvesting by seaweed pickers. The *Sargassum* cycle in the Philippines was reported by **Calumpong *et al.* (1999)**, who stated that June-August is a slow growth period, followed by a fast growth period in September-October, and November-March is a reproductive period. In contrast, the senescence period occurs in April-May **(Calumpong *et al.*, 1999)**. This differs from the reproduction of *S. fusiformis* reported by **Yoshida *et al.* (2017)**, where receptacle formation occurs in June-July (**Yoshida & Shimabukuro, 2017**). This shows that differences in species and environmental conditions can affect the *Sargassum* cycle. The study's results on *S. ilicifolium* in the Southern Islands of Singapore showed that the thallus reached its maximum length in December (110.39 ± 2.37cm) during the cold water temperature period. The minimum length occurred in May (9.88 ± 0.48cm) during the warm water temperature period **(Low *et al.*, 2019b)**. The results of our study are also in line with studies on *S. horneri* and *S. fusiforme* that the growth period (fast growth) occurs in August-November. In contrast, slow growth occurs in February-April **(Arenas & Fernández, 2000)**. The monitored area of *Sargassum* shows fluctuations and patterns that change every year. The biomass calculation predictions in this study cannot yet indicate the biomass weight in each growth period or location because the SI value variable indicating the intensity of *Sargassum* presence is not included in the biomass calculation. As a result, throughout 2020-2023, it shows the same pattern as the area of *Sargassum*. However, this biomass is important for predicting economic value in Gunungkidul waters.

4. The effect of microclimate on the growth of *Sargassum* spp.

Microclimate is one of the factors that influence the growth and distribution of macroalgae in waters. In a complex way, microclimate affects biological processes through physiological processes such as photosynthesis, respiration, enzyme activity, seed germination and senescence, and even the ability to regenerate, grow, and distribute plants on land and in waters **(Brosofske *et al.*, 1997)**. *Sargassum* growth is significantly affected by the spatio-temporal water conditions at its specific cultivation site **(Sumandiarsa *et al.*, 2021)**. In order to assess the impact of the environment on the growth and distribution of *Sargassum*, this study limited its measurements to the environmental conditions above sea level. The correlation coefficient analysis was conducted at a 95% confidence level and revealed a statistically significant negative relationship between humidity and the SI value (Table 2). However, the variables of SST, lighting duration, wind speed, TSS, and rainfall did not significantly impact the SI, NDVI, and area values.

Humidity is the only significant factor that has a negative effect on the SI value in Gunungkidul waters. This analysis demonstrates that elevated humidity levels lead to a reduction in the SI value. This condition explains that high humidity can affect *Sargassum*'s growth, ultimately affecting its presence along the waters. This is possible because high humidity can increase rainfall, which can reduce salinity and reduce the rate of photosynthesis because sunlight is blocked by clouds caused by high humidity. Elevated humidity levels will also impact the rise in sea surface temperature, potentially influencing *Sargassum*'s development in exceptionally severe circumstances. SI>1 and

NDVI>0.1 values are almost evenly distributed in June with 85-89% humidity. This figure illustrates the ideal development of *Sargassum* within a humidity range of 85-89%. **Chia and Lim (2022)** conducted research indicating that plants require relative humidity within the range of 85±2% for optimal functioning. Suboptimal conditions will increase stomatal resistance, which causes reduced carbon dioxide absorption and photosynthesis rate. Conversely, if it is too high, it will reduce the transpiration rate, which causes reduced nutrient absorption **(Chia & Lim, 2022)**.

SST, lighting duration, wind speed, TSS, and rainfall are positively correlated with SI and NDVI values. This means that an increase in the value of these environmental parameters causes an increase in SI and NDVI values. This can happen because environmental conditions in Gunungkidul are within the suitable range for the growth of *Sargassum*. However, from the correlation results (r), SST has the strongest positive correlation with the area of *Sargassum*. This means that increasing SST will increase the area. SST is the temperature of water approaching the surface with a thickness of 10μm **(Emery, 2015)**. SST is a significant determinant that can alter marine ecosystems by impacting plant, animal, and microbial species in the area and endangering vulnerable marine life like corals. This, in turn, affects nutrient availability and threatens algae growth **(Ostrander *et al.*, 2000; Pratchett *et al.*, 2004; Pershing *et al.*, 2018)**.

The ideal temperature range for macroalgae growth is often between 20 and 30°C **(Singh & Singh, 2015)**. In 2020-2022, the average annual temperature ranged from 25-29°C (Table 1). The dynamics of wind and currents greatly influence this condition. During the eastern season, characterized by a strong upwelling in the southern waters of Java, the temperature will decline to 26.0-27.5. Significant monthly SST variations were seen in 2020, but no notable change was seen in the subsequent two years (Table 1). Entering the transition season, the temperature usually increases due to the decreasing influence of upwelling **(Perikanan & Kelautan, 2022)**. Based on direct field observations, the SST did not exhibit a notable disparity with the average water temperature in Gunungkidul (26.5-29.8°C). The water temperatures in Gunungkidul remain within the range necessary for the growth of *Sargassum*. According to **Kadi (2005)**, the optimum temperature for *Sargassum* growth ranges from 27.25-29.30°C in Indonesia. While not statistically significant, the findings of our investigation also indicate a robust positive association (Table 2). For example, in March-April, the increase in SST is linear with the increase in the area of growth, as well as in the periods Jan-Feb and Mar-Apr (Table 1 & Fig. 7). The increase in temperature is still within the temperature range for *Sargassum* growth, so it does not affect the area of *Sargassum* growth. Temperature is an important environmental factor in supporting growth as it influences all biological processes, ranging from molecules to ecosystems, enabling their survival, development, and reproduction. In addition, temperature can also affect the morphology and distribution of macroalgae populations. The theory of the dependence of enzyme reaction rates on temperature forms an exponential function by identifying the optimal temperature (around 25°C) **(Arroyo *et al.*, 2022; Geppi & Riera, 2022)**. Previous studies have reported that each Sargassum species has a different temperature tolerance ability; for example, *S. polycystin* has an optimal growth temperature between 20-25°C and will be disturbed if the seawater temperature is > 30°C **(Hwang *et al.*, 2004)**. Optimal growth of *S. ilicifolium* occurs throughout winter when temperatures range from 28 - 30°C. In locations with lower maximum temperatures, it can even maintain relatively high biomass throughout the year **(Ateweberhan *et al.*, 2005)**. The development of *S. aquifolium* is most favorable at temperatures ranging from 23 to 30°C. A similar finding was reported in the Korean Peninsula, postulating that the sea level (SST) is the most influential environmental variable in the distribution of *S. horneri* **(Shin *et al.*, 2022)**.

The duration of sunlight in the waters is closely related to SST. Correlation analysis shows a positive relationship between the duration of sunlight and SI, NDVI, and area. The duration of sunlight directly impacts *Sargassum*'s water temperature and photosynthetic capacity. Specifically, longer durations of sunlight result in higher water temperatures, which alter the intricate process of natural photosynthesis. Ultimately, this has implications for the sustainability of *Sargassum* growth and reproduction. Moderate sunlight is required to stimulate the growth of *Sargassum* **(Shin *et al.*, 2022)**. The study's environmental parameter data revealed that the January-February, March-April, and August-September periods had the longest peak sunshine duration, reaching 9.9 hours per day (Table 1). This resulted in an elevation of sea surface temperature (SST). These water conditions can support the growth and reproduction of *Sargassum* in Gunungkidul, which is reinforced by the results of a positive correlation with the SI, NDVI, and area parameters (Table 2).

Rainfall in waters can have a direct effect by reducing salinity. On the other hand, when salinity decreases, ocean stratification will increase, and vertical mixing will be restrained, which results in unstable temperature and salinity **(Liu *et al.*, 2020)**. Research results in Bali waters reported that rainfall is related to SST. SST typically exhibits higher values during the rainy season compared to the dry season **(Martini *et al.*, 2021)**. There are often two wet months (rainy season) in Gunungkidul, namely March and October-December, but this condition varies according to the global climate. The findings of our study indicate a negative correlation between precipitation, SI, NDVI, and the *Sargassum* area. In addition to shortening the lighting duration, heavy rains can harm the *Sargassum* thallus, resulting in its fragmentation or destruction. Rainwater infiltration into the waterways might decrease salinity, impeding *Sargassum*'s growth. Macroalgae fragments increase TSS values, indicating higher particles in the water. However, this rainy season also causes higher temperatures in the ocean, which encourages both vegetative and generative reproduction.

In general, in the correlation analysis between environmental factors and SI interpolation values, NDVI and growth area yield more non-significant results. This indicates a weaker relationship between the measured vegetation index and environmental factors. The observed phenomenon can be attributed to the intricate interplay between vegetation dynamics and other environmental factors, such as pH, salinity, water temperature, nutrients, and anthropogenic activities, which were not considered in this study. Seaweed pickers in Gunungkidul engage in mass harvesting of macroalgae from August to October and December to April the following year. This activity is believed to contribute to fluctuations in the vegetation index, thereby complicating the interaction. However, initial information on mapping the presence of macroalgae along the coast of Gunungkidul is essential to determine the presence of Sargassum and its year-round productivity. This information will enable pickers and policymakers to properly utilize the natural potential and implement conservation measures while ensuring the long-term viability of the aquatic ecosystem.

5. Biomassa of *Sargassum* spp.

The growth of terrestrial plant biomass usually follows a positive correlation pattern. Biomass will increase when the temperature increases. In contrast, marine primary producers usually follow the opposite pattern. Biomass will increase when the environmental temperature decreases. In *Sargassum*, fast growth occurs from August to November, while slow growth occurs from February to April **(Arenas & Fernández, 2000; Huston & Wolverton, 2009; Marzinelli *et al.*, 2015)**. *Sargassum* biomass sampling was conducted in November-October 2022, during the peak harvest season in Gunungkidul waters. The sampling results at ten sites in Gunungkidul waters exhibited nearly uniform values, ranging from 9.67 to 15.83kg/ m^2. The mean biomass on the ten beaches was around 11.96 ± 1.83kg/ m^2 by wet weight (Table 3). Several previous studies have reported that *Sargassum* biomass shows diversity in Indonesian waters. On the South coast of Gunungkidul, *Sargassum* reaches 5-15 tons/km^2; in the Sunda Strait, it ranges from 5-10 tons/km^2 **(Kadi, 2004)**. In Lampung Bay, *Sargassum* biomass reaches 35-57.5 g/m^2, while in the waters of Prigi Bay, Trenggalek, *S. polycystum* has a biomass of 17.55 g/m^2 **(Kadi, 2015)**. For Poncan Gondang Island, North Sumatra, the biomass ranges from 96.96-163.54 g/m^2 **(Hutapea *et al.*, 2022**). Research in Shoalwater Islands Marine Park, south of Perth, reported *Sargassum* biomass ranging from 4.25 kg/m^2 to 1.04 kg/m^2 **(Hoang *et al.*, 2016)**.

In Australia, the average biomass of *S. thunbergii* and *S. fusiforme* reached 2,027.95 ± 590.93 and 1,897.13 ± 404.58g/ m^2 **(Chen *et al.*, 2022)**. Unpublished research stated that at Trenggole Beach, Gunungkidul, in May-August 2022, the *S. polycystum* species had a 36.8814 g/m^2 biomass.

Thermal conditions are of utmost importance in macroalgae as they directly impact metabolic processes such as nutrition absorption rate, photosynthesis, and respiration. The rate of nutrient absorption will increase with increasing temperature under natural conditions **(Yamamoto & Takao, 1988; Lobban & Harrison, 2000)**. SST is one of the main contributors to the pattern of marine primary producers, which generally increases when temperatures decrease **(Huston & Wolverton, 2009; Marzinelli *et al.*, 2015)**. Sargassum biomass has been reported to decrease with increasing sea surface temperature (SST) **(Hoang *et al.*, 2016)**. However, our study shows a positive correlation: as biomass decreases, SST increases. We predict this is because SST in Gunungkidul waters (26-30.33°C) still meets the requirements for *Sargassum* growth (25-30°C). Therefore, the elevated temperatures in Gunungkidul are still conducive to *Sargassum* growth.

The mean mass of *Sargassum* biomass in our study exceeded that of previous studies. Factors such as humidity, SST, light, rainfall, total suspended solids (TSS), wind speed, and symbiosis with coral reefs in Gunungkidul waters create a favorable environment for the growth and reproduction of *Sargassum*, particularly during certain seasons. These findings support the notion that temperature is not the sole determinant of algal biomass; additional factors, such as wave action and nutrient concentrations, also play a significant role **(Kraufvelin *et al*., 2010)**.

CONCLUSION

Analysis of average climatic data from 2020 to 2022 in Gunungkidul waters indicates favorable conditions for *Sargassum* spp. growth, particularly during January-February, March-April, and August-September. The growth pattern of *Sargassum* in Gunungkidul is estimated as follows:

- **January-February**: Thallus growth begins from filamentous holdfasts.
- **March-May**: Continued growth from holdfasts and fragmentation results in high Sargassum Index (SI) values and area coverage.
- **June-July**: Thalli are found only in specific locations with minimal human activity, primarily as *Sargassum* seeds, marking the onset of slow vegetative and generative growth.
- **August-October**: Rapid growth of Sargassum seeds to adulthood occurs.
- **November-December**: Growth begins to decline due to harvesting activities.

Mapping of NDVI and SI values reveals *Sargassum* habitats in areas such as Ngunggah, Ngrenehan, Kukup, Sepanjang, Watu Kodok, Drini, Betueng, Krakal, Sadranan, Trenggole, and the eastern part around Dadapan Beach. These regions share characteristics of dead, massive, steep, and coarse sandy rocks.

The average weight of *Sargassum* biomass in Gunungkidul waters shows higher wet weights compared to various locations in Indonesia and Asia. These findings suggest that the growth of biota in these waters is influenced by a complex interplay of large-scale natural factors, such as microclimate and physical chemistry, the symbiosis between *Sargassum* and coral reefs, and anthropogenic activities in the surrounding areas. Further investigation is needed to better understand this phenomenon.

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