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Mapping seagrass distribution in Gili Mantra National Conservation Area, Indonesia, using Sentinel 2A imagery

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Abstract. *Jamil K, Najih MR, Hawati, Suleman Y, Mustafa, Awaluddin, Rahmaniar N, Aisyah N. 2025. Mapping seagrass distribution in Gili Mantra National Conservation Area, Indonesia, using Sentinel 2A imagery. Biodiversitas 26: 4324-4333.* Indonesia, an archipelagic country dominated by coastal areas, possesses high biodiversity and abundant natural resources. Among these, seagrass ecosystems play a vital ecological role by providing habitat, supporting marine biodiversity, and stabilizing coastal sediments. Gili Trawangan Island, located in North Lombok District, West Nusa Tenggara Province, Indonesia, is surrounded by extensive seagrass beds. However, increasing anthropogenic activities have altered environmental conditions, leading to reduced water quality and degradation of coastal ecosystems, including seagrass habitats. This study aimed to assess the distribution and composition of seagrass beds on Gili Trawangan Island over the past two years. Field surveys were conducted from January to March 2024 using a quadrat-transect method, with 100 m transect lines laid perpendicular to the coastline and sampling performed with 50×50 cm^2 frames at 10 m intervals. Satellite imagery from Sentinel-2A was also processed to complement field observations. Three seagrass species were recorded: *Cymodocea rotundata*, *Thalassia hemprichii*, and *Halodule pinifolia*. *Cymodocea rotundata* showed the highest density at all four sampling stations, whereas *T. hemprichii* exhibited the lowest. Seagrass coverage declined markedly from approximately 75 ha in 2022 to 44 ha in 2023. These findings provide essential baseline information for the sustainable conservation and management of seagrass ecosystems in Gili Trawangan.

Keywords: *Cymodocea rotundata*, density, Gili Trawangan, habitat monitoring, remote sensing

INTRODUCTION

Indonesia possesses vast marine resources in terms of both quantity and biodiversity (Hutomo and Moosa 2005; Widayanti et al. 2022; Basyuni et al. 2024). Among these, seagrass is a valuable resource with great ecological and socio-economic importance. Seagrasses are high-level, flowering plants (Angiospermae) that have adapted to live fully submerged in marine environments (Orth et al. 2006; Fitrian et al. 2017; Risandi et al. 2023). By 2017, the validated extent of seagrass ecosystems in Indonesian waters reached 150,693.16 ha (LIPI 2018). This extensive distribution reflects the high diversity of seagrass meadows in the Indonesian archipelago, which hosts more than 12 species (Sondak and Kaligis 2022). These species differ in morphology and ecological function, enhancing habitat complexity and supporting diverse faunal communities (Castro-Fernández et al. 2025).

Seagrasses typically grow in shallow tropical waters where sunlight penetrates sufficiently for photosynthesis (Zimmerman 2007; Risandi et al. 2023). Ecologically, they stabilize seabed substrates, reduce wave energy, lower turbidity, and serve as critical habitats and nursery grounds for numerous marine species, including fish, mollusks, and other invertebrates (Fahruddin and Ilyas 2023). Beyond supporting marine biodiversity, seagrasses contribute to climate regulation through carbon sequestration, storing substantial amounts of carbon in their biomass and sediments (Kuwae et al. 2022; Supratman et al. 2024). Maintaining healthy seagrass beds is therefore essential, which requires regular monitoring and management to prevent degradation. Declines in seagrass coverage have been linked to nutrient loading, sedimentation, toxic chemical exposure, maritime activities, coastal reclamation, mangrove deforestation, and waste disposal (Unsworth et al. 2018).

Monitoring seagrass distribution and condition is a fundamental aspect of sustainable management. Remote sensing has emerged as an effective approach for seagrass ecosystem mapping, utilizing satellites equipped with sensors to capture imagery of the Earth's surface (Machireddy 2023). This method enables the timely and accurate collection of data across large and often inaccessible areas (Kofidou 2024). Through satellite image analysis, variations in seagrass coverage can be detected based on differences in substrate color and texture (Sabilah et al. 2021), facilitating the identification of areas experiencing decline or expansion.

In addition to their ecological functions, seagrass ecosystems provide direct and indirect benefits to coastal communities, including supporting fisheries productivity, protecting shorelines, and offering opportunities for eco-tourism (Inocentes et al. 2025; Nyangoko et al. 2025). According to Sondak and Kaligis (2022), these benefits can be sustained only through management strategies that respond effectively to environmental changes, whether indicating improvement or decline in seagrass health.

The Gili Matra Marine Tourism Park, encompassing Gili Meno, Gili Air, and Gili Trawangan, exemplifies an area where seagrass conservation is critical. Located in North Lombok District, West Nusa Tenggara Province, Indonesia, this national conservation area spans approximately 2,268.59 ha and is renowned for its white sandy beaches, clear waters, and coral reefs that support diverse fish species (Rahmi et al. 2025). Gili Trawangan, in particular, has experienced rapid growth in tourism and coastal activities, raising concerns about environmental degradation, including potential losses in seagrass cover.

The latest assessment of seagrass distribution in Gili Trawangan is crucial for evaluating the impact of anthropogenic pressures on coastal ecosystems. Seagrass bed mapping and monitoring of temporal changes not only support conservation planning but also strengthen the sustainability of the local economy, which is heavily dependent on marine-based tourism and fisheries. The integration of field surveys with satellite monitoring produces spatially accurate and temporally relevant data, providing valuable references for local governments, stakeholders, researchers, communities, academics, non-governmental organizations, the tourism sector, traditional fishermen, the fishing industry, environmental regulators, policy makers, and conservation organizations to design effective management, rehabilitation, protection, mitigation, adaptation, education, monitoring, restoration, innovation, and collaboration strategies for seagrass ecosystems in Gili Trawangan and other coastal areas of Indonesia.

MATERIALS AND METHODS

Study area

This study was conducted from January 15 to March 31, 2024, under the Kupang National Marine Conservation Area Office, specifically within the Gili Matra Island Conservation Area Work Unit, which includes Gili Meno, Gili Air, and Gili Trawangan in North Lombok District, West Nusa Tenggara Province, Indonesia. Field data collection focused on Gili Trawangan, located in Pemenang District, North Lombok District, West Nusa Tenggara. The study area map is presented in Figure 1.

Procedures

Types and sources of data

This study utilized both primary and secondary data sources. Primary data were obtained through direct field observations, including seagrass data collection. Secondary data were derived from remote sensing imagery obtained from publicly accessible satellite databases.

Data collection methods

Two main methods were employed for data collection. The first involved direct field observations to document seagrass distribution and related environmental parameters. The second involved remote sensing data processing to map and analyze seagrass coverage. The overall data collection procedure is illustrated in Figure 2.

Field data collection

Seagrass identification in the waters of Gili Trawangan Island was conducted using the quadrat transect technique (straight-line transect) adapted from the Seagrass-Watch protocol and CORMEP-LIPI guidelines. Four sampling stations were established around the island, each with five transects, resulting in a total of 20 transects for the study. At each station, a 100 m measuring tape was laid perpendicular to the shoreline, with 50 m spacing between adjacent transects. Along each transect, quadrats measuring 50×50 cm² were placed at 10 m intervals on the right-hand side. Within each quadrat, species composition, percentage cover, and substrate type were recorded.

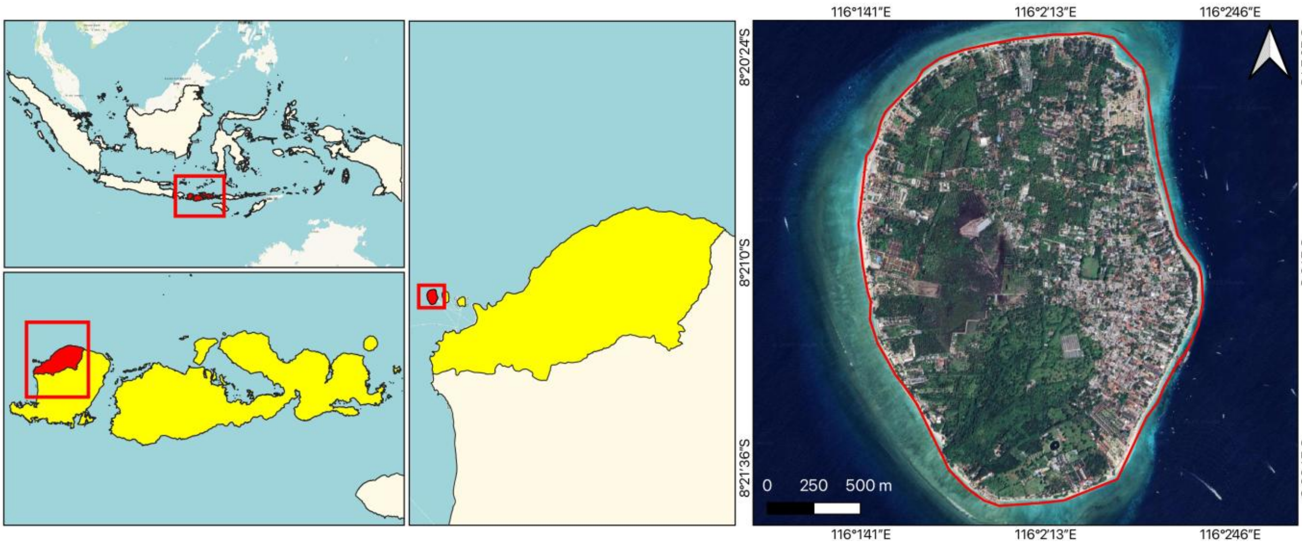

Figure 1. Research location map showing the position of Gili Trawangan Island (latitude 8°20′N and longitude 116°00′-116°08′E) within the Gili Matra National Marine Conservation Area, North Lombok District, West Nusa Tenggara Province, Indonesia

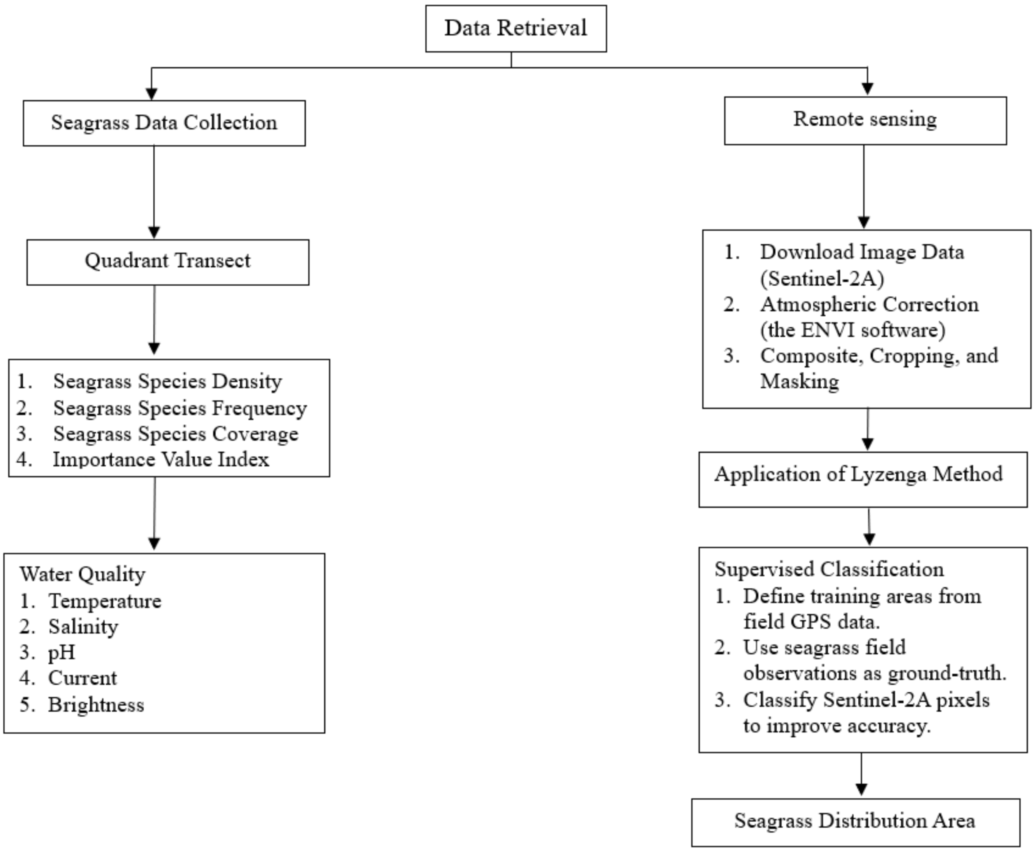

Figure 2. Procedure for seagrass data collection and supervised classification of Sentinel 2A data

Field surveys were carried out during low tide to ensure optimal access and safety, with tidal schedules determined from local information or official charts. Before sampling, field worksheets were completed with observer names, station codes, transect numbers, dates, times, and other relevant details. The starting point of each transect was marked with an iron or wooden stake fitted with a buoy, and its coordinates were recorded using GPS. Observers then stretched the measuring tape in a straight line perpendicular to the shoreline, placing the first quadrat at the 0 m mark. While moving along the transect, the observer walked on the opposite side of the tape from the quadrats to prevent disturbance to the sampling area. Seagrass cover within each quadrat was visually estimated using the smaller subdivisions of the frame, and substrate was classified as muddy, sandy, or rubble. Observations were repeated every 10 m until reaching 100 m or the edge of the meadow, with the endpoint marked and its coordinates recorded. This procedure was repeated for each transect at all stations.

Image data processing

There are several steps involved in processing remote sensing data, as outlined: (i) Download satellite imagery: The imagery used in this Final Practical Work (KPA) is Sentinel-2A Level-1C data. The satellite images were downloaded from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). When downloading the images, it is important to consider the cloud cover percentage, as lower cloud coverage facilitates easier and more accurate image processing; (ii) Atmospheric correction: This step aims to eliminate atmospheric effects that can obscure or distort the image. Atmospheric correction was performed using the ENVI software. This process helps remove pixel value variations caused by sea surface or atmospheric scattering, typically using the Near-Infrared (NIR) band (Purwanto et al. 2019); (iii) Band composition, cropping, and masking: After atmospheric correction, the next step is band composition, which involves combining multiple spectral bands into a composite image to enhance color contrast and facilitate visual analysis. This is followed by cropping, where the image is trimmed to focus on the area of interest, making subsequent processing more efficient. Finally, masking is applied to distinguish between land and water areas. This helps isolate and analyze underwater features more effectively; (iv) Lyzenga method: The Lyzenga method is applied to enhance the identification of underwater objects. It uses a specific algorithm to separate different benthic features based on reflectance values. This method allows for the detection of objects such as sand, coral reefs, and seagrass beds; (v) Image classification: This study employs a supervised classification approach. The first step involves defining a training area by visiting several field sites and recording their coordinates. Field observations are then used to classify and label satellite image pixels based on the identified features. The collected field data are incorporated into the image analysis to improve classification accuracy.

Data analysis

Data analysis in this study comprised both seagrass data processing and remote sensing-based image interpretation. Seagrass species density was calculated to assess seagrass condition categories, while species frequency was used to determine distribution patterns. Species cover was measured to quantify the percentage of substrate occupied by each species. The Importance Value Index (IVI) was then computed to evaluate the ecological role of each species within the community, incorporating relative density, frequency, and cover.

For remote sensing analysis, the Lyzenga Algorithm was applied to extract benthic substrate information by calculating the ratio coefficient between the green (Band 3) and blue (Band 2) spectral bands. The process began with a statistical analysis to determine the coefficient a, calculated using:

$$a = \frac{Varian\ B2 - Varian\ B3}{Covarian\ B2, B3}$$

Where, Varian B2 and Varian B3 refer to the variance of reflectance values in Bands 2 and 3, respectively, while Covarian B2, B3 represents their covariance. Variance and covariance values were obtained using Microsoft Excel.

After determining a, the coefficient ratio ki/kj was calculated and applied to the Lyzenga transformation:

$$Y = In(Li) - [(\frac{ki}{kj}) \times In(LJ)]$$

Where, Y is the basic substrate extraction result, Li is the blue band (Band 2) reflectance, Lj is the green band (Band 3) reflectance, ki/kj is the coefficient ratio between the green and blue bands, and ln denotes the natural logarithm.

RESULTS AND DISCUSSION

Seagrass species found on Gili Trawangan Island

Lombok Island, located in the eastern part of Indonesia, is surrounded by numerous small islands locally known as "Gili" Among these, Gili Trawangan is one of the most popular and frequently visited. The island measures approximately 3 km in length and 2 km in width, with a total area of 2,954 m^2, and lies between latitude 8°20′N and longitude 116°00′-116°08′E. Its geographical position places it in direct contact with open ocean waters, forming an important coastal ecosystem.

Field surveys conducted in the waters surrounding Gili Trawangan identified three seagrass species (Table 1). These species represent the dominant seagrass community in the area and form critical habitats that support local marine biodiversity.

Table 1 shows the distribution of seagrass species across the four sampling stations on Gili Trawangan Island. Stations 1 and 2 each contained three species: *Cymodocea rotundata* Asch. & Schweinf., *Thalassia hemprichii* (Ehrenb. ex Solms) Asch., and *Halodule pinifolia* (Miki) Hartog. In contrast, Stations 3 and 4 supported only two species, *C. rotundata* and *T. hemprichii*. The absence of *H. pinifolia* at Stations 3 and 4 is likely due to unsuitable habitat conditions. These sites were characterized by sandy substrates mixed with abundant coral fragments, which are less favorable for *H. pinifolia* growth. According to Tupan and Uneputty (2018), *H. pinifolia* generally thrives in shoreline environments with sandy or muddy substrates, conditions not prevalent in these locations.

Seagrass density

The density of seagrass species is influenced by several environmental factors, including water depth, light availability, and substrate type. Generally, seagrass growing in deeper and clearer waters tends to have higher densities than those in shallow or turbid conditions.

At Station 1, *C. rotundata* recorded a density of 864.4 ind·m^{-2}, *T. hemprichii* 12 ind·m^{-2}, and *H. pinifolia* 766.9 ind·m^{-2}. At Station 2, *C. rotundata* showed the highest density across all sites with 1265.5 ind·m^{-2}, followed by *T. hemprichii* with 4 ind·m^{-2}, and *H. pinifolia* with 50.5 ind·m^{-2}. At Station 3, *C. rotundata* was recorded at 573.1 ind·m^{-2}, while *T. hemprichii* reached 7.6 ind·m^{-2}. Finally, at Station 4, *C. rotundata* had a density of 766.9 ind·m^{-2}, and *T. hemprichii* at 72 ind·m^{-2}. The distribution of seagrass density across stations is illustrated in Figure 3.

Table 1. Seagrass species found at four sampling stations around Gili Trawangan Island, West Nusa Tenggara Province, Indonesia

Seagrass	Station			
	1	2	3	4
Cymodocea rotundata (Cymodoceaceae)	+	+	+	+
Thalassia hemprichii (Hydrocharitaceae)	+	+	+	+
Halodule pinifolia (Cymodoceaceae)	+	+	-	-

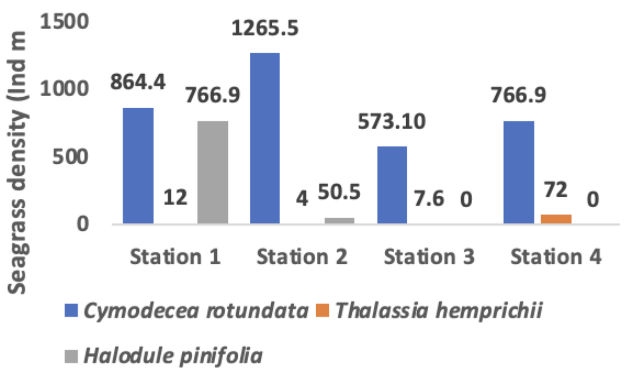

Figure 3. Seagrass density of Gili Trawangan Island, West Nusa Tenggara Province, Indonesia

At Station 1, *C. rotundata* exhibited the highest density (864.4 ind·m^{-2}), while *T. hemprichii* had the lowest (12 ind·m^{-2}). The high density of *C. rotundata* is likely due to favorable environmental conditions, as the waters surrounding Gili Trawangan Island maintain temperatures between 30-31°C, which fall within the optimal range for seagrass growth (28-35°C). In contrast, the low density of *T. hemprichii* at this station may be attributed to anthropogenic pressures, such as solid waste pollution, which can physically damage seagrass beds and impair their growth. Additionally, fluctuations in water quality parameters, including temperature, salinity, and currents, may further contribute to reduced density (Rothing et al. 2023).

At Station 2, *C. rotundata* reached its highest recorded density across all stations (1265.5 ind·m^{-2}), while *T. hemprichii* remained low at 4 ind·m^{-2}. At Station 3, *C. rotundata* recorded a density of 573.1 ind·m^{-2}, with *T. hemprichii* at only 7.6 ind·m^{-2}. Similarly, Station 4 showed *C. rotundata* at 766.9 ind·m^{-2} and *T. hemprichii* at 72 ind·m^{-2}. Based on established categorization criteria (Rosalina et al. 2023), *C. rotundata* falls into the "very dense" category, *T. hemprichii* ranges from "sparse" to "very dense," and *H. pinifolia* ranges from "very sparse" to "very dense." The low density of *T. hemprichii* at Station 4 may be linked to habitat preferences, as this species thrives in shallow waters with sandy substrates (Rombe et al. 2022).

Cymodocea rotundata consistently exhibited the highest density across all stations, with the peak at Station 2. Its abundance is likely supported by substrate characteristics, as this species prefers sandy bottoms but also grows well in areas with coral fragments (Djafar and Mamu 2022). Indeed, all stations where *C. rotundata* occurred had substrates ranging from sand to coral rubble.

Halodule pinifolia was the second most abundant species, with a wide distribution and rapid growth on sandy to muddy substrates (Septiani et al. 2022). The substrate variability in Gili Trawangan Island, from muddy sand to coral fragments provide favorable conditions for the establishment of multiple seagrass species.

Frequency of seagrass species

The frequency of seagrass species reflects the likelihood of encountering each species within sampling plots and serves as an indicator of their spatial distribution. According to Ningtasya et al. (2020), species frequency is strongly influenced by substrate type, as different species have specific substrate preferences.

At Station 1, *C. rotundata* had a frequency of 0.189 while both *T. hemprichii* and *H. pinifolia* had a frequency of 0.005. At Station 2, *C. rotundata* remained high at 0.206, *T. hemprichii* decreased to 0.003, and *H. pinifolia* was 0.031. At Station 3, *C. rotundata* recorded 0.098 and *T. hemprichii* 0.008. At Station 4, *C. rotundata* again reached 0.166, while *T. hemprichii* was 0.048. The frequency patterns across stations are presented in Figure 4.

Based on observations, *C. rotundata* exhibited the highest frequency at all stations, ranging from 0.098 to 0.206. In contrast, the lowest frequencies varied by location: at Station 1, *T. hemprichii* and *H. pinifolia* both recorded a frequency of 0.005; at Station 2, *T. hemprichii* was lowest with 0.003; at Station 3, *T. hemprichii* again had the lowest value (0.008); and at Station 4, *T. hemprichii* recorded 0.048. Both *C. rotundata* and *T. hemprichii* demonstrated broad distribution across stations, appearing in nearly all observation quadrats (Hartati et al. 2017). According to Fernando et al. (2019), these two species are more abundant in areas with optimal environmental conditions, such as normal brightness levels, stable temperatures, and moderate currents, conditions characteristic of Stations 1 and 2. The high frequency of *C. rotundata* is also supported by the prevailing water temperature of around 30°C, which is well within the species' preferred range (Rombe et al. 2022). In general, a greater number of seagrass species at a station correlates with higher frequency values, reflecting the adaptability of these species to grow under varying environmental conditions (Ansal et al. 2017).

Seagrass cover

Seagrass cover represents the proportion of substrate area occupied by seagrass within a given water body. This percentage is influenced not only by the density of individual species but also by leaf morphology, as wider leaves provide greater substrate coverage (Fahruddin and Ilyas 2023). Field measurements at the four observation stations showed variation in species cover. At Station 1, *C. rotundata* covered 8.89% of the substrate, *T. hemprichii* 0.18%, and *H. pinifolia* 0.25%. At Station 2, *C. rotundata* exhibited the highest coverage at 11.45%, followed by *H. pinifolia* at 1.36% and *T. hemprichii* at 0.12%. At Station 3, C. rotundata covered 5.79%, while *T. hemprichii* accounted for 0.29%. At Station 4, *C. rotundata* and *T. hemprichii* each covered 1.70% of the substrate whereas the species *H. pinifolia* was not found at this Stations 3 and 4 (Figure 5).

The predominance of *C. rotundata* and *T. hemprichii* across stations reflects their high substrate suitability and adaptability to varying environmental conditions (Fitrian et al. 2017). Both species demonstrate efficient nutrient absorption across different substrate types, supporting their persistence. *C. rotundata*, in particular, has a relatively larger leaf size compared to species such as *Syringodium isoetifolium* (Rosalina et al. 2022), which increases its capacity to cover substrate.

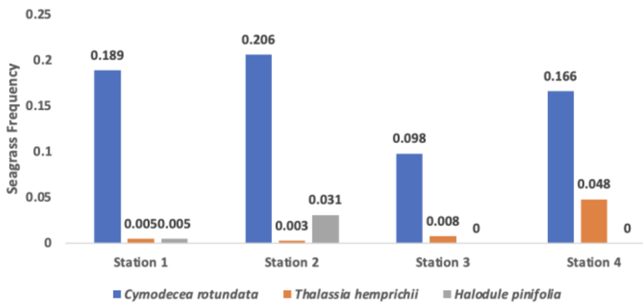

Figure 4. Frequency value of seagrass in Gili Trawangan Island, West Nusa Tenggara Province, Indonesia

Variations in seagrass cover are likely influenced by nutrient availability, which tends to decrease in areas closer to open sea, as well as by hydrodynamic factors such as tidal exposure. High densities combined with low tide during sampling can reduce estimated cover values. *Thalassia hemprichii*'s higher cover relative to *H. pinifolia* is consistent with its broader leaves, which contribute to greater substrate coverage.

The index of importance

The Index of Importance (INP) represents the sum of relative density, relative frequency, and relative cover, providing an integrated measure of a seagrass species' ecological role within a community (Rosalina et al. 2022). This index reflects the prominence of each species relative to others at the study site, with higher values indicating greater ecological significance.

At Station 1, *C. rotundata* recorded the highest INP value of 2.434, followed by *H. pinifolia* with 0.516, while *T. hemprichii* had the lowest value of 0.05. Station 2 showed a similar pattern, with *C. rotundata* again dominating with a value of 2.702, *H. pinifolia* with 0.272, and *T. hemprichii* with 0.027. At Station 3, *C. rotundata* remained dominant with an INP value of 2.864, far exceeding *T. hemprichii*, which recorded 0.136. In contrast, Station 4 showed an INP value of 2.497 for the species *C. rotundata* and *T. hemprichii* with a value of 0.503. This can be seen in Figure 6.

These results indicate that *C. rotundata* is the most ecologically important seagrass species across most stations, consistent with its high density, frequency, and cover observed in previous analyses. The relatively low INP values for *T. hemprichii* and *H. pinifolia* suggest a more limited role in structuring the seagrass community, although their presence contributes to species diversity and potential ecological resilience of the habitat.

Figure 6 illustrates that *C. rotundata* consistently recorded the highest INP across all stations, highlighting its dominant ecological role in the seagrass community. At Station 1, *C. rotundata* achieved an INP of 2.434, while *T. hemprichii* recorded the lowest value at 0.05. A similar pattern was observed at Station 2, where *C. rotundata* reached 2.702 and *T. hemprichii* dropped to 0.027. At Station 3, *C. rotundata* further increased to 2.864, with *T. hemprichii* at 0.136. Station 4 maintained the same trend, with *C. rotundata* at 2.497 and *T. hemprichii* at 0.503. The consistently high INP values for *C. rotundata* reflect its strong adaptability and competitive advantage in the prevailing environmental conditions. As noted by Adi et al. (2015), *C. rotundata* thrives in sandy substrates, a habitat type that is abundant in the study area, which likely supports its dominance.

Water quality parameters

Water quality plays a crucial role in the survival of aquatic organisms, as it directly affects their abundance and distribution (Tomascik et al. 1997; Fahruddin and Ilyas 2023). According to Latuconsina et al. (2014), the condition of seagrass meadows is strongly influenced by the physical and chemical parameters of the surrounding waters and the characteristics of their habitat. The water quality measurements recorded around Gili Trawangan Island are summarized in Table 2.

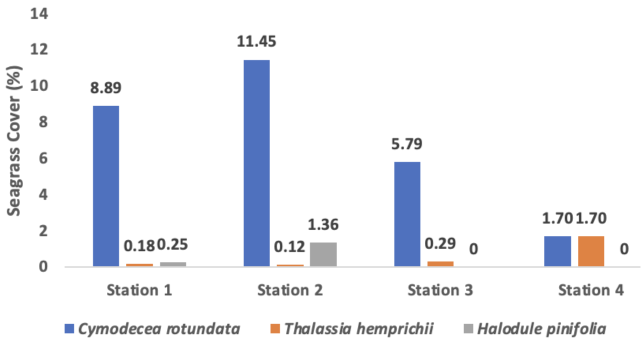

Figure 5. Seagrass closure value of Gili Trawangan Island, West Nusa Tenggara Province, Indonesia

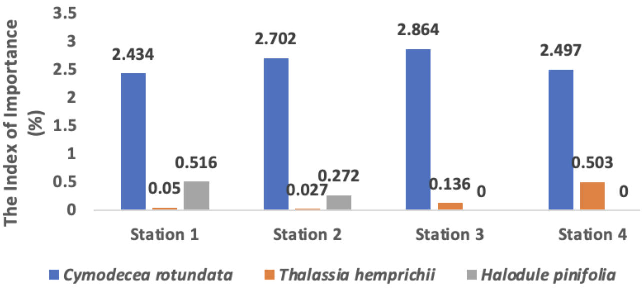

Figure 6. The Index of importance of seagrass species in Gili Trawangan Island, West Nusa Tenggara Province, Indonesia

Table 2. Water quality parameters

Parameters	Unit	Station 1	Station 2	Station 3	Station 4
Temperature	ºC	30-31	30-32	29-31.5	29.5-31
pH	-	7-7.8	7.8-8	7.5-8.1	7.3-8
Salinity	ppm	31-33	30-31	32-33	30-31
Current	m s^{-1}	0.13-0.14	0.13-0.16	0.14-0.16	0.14-0.16
Substrate	-	Sand-Rubble	Sand	Sand-Rubble	Sand-Rubble

Temperature in the study area ranged from 29-32°C, with an average of 30.5°C. The highest temperatures were recorded at Stations 1 and 2 (30-32°C), while the lowest were observed at Stations 3 and 4 (29-31.5°C). According to Indonesian Ministry of Environment Number 51 of 2004, the optimal temperature range for seagrass growth is 28-30°C, indicating that the recorded temperatures were generally above the recommended limit. The elevated temperatures were likely due to data collection being conducted during midday at low tide, when surface heating is more intense. Elevated temperatures can influence the photosynthetic efficiency of seagrasses, potentially affecting their growth and distribution.

The pH values ranged between 7.0 and 8.1 across the four stations, falling within the optimal range for seagrass growth (7.0-8.5) as outlined in Government Regulation of the Republic Indonesia (PPRI) of Number 22 of 2021. Variations in pH between stations may be attributed to differences in depth and biological activity, particularly photosynthesis and respiration, which influence carbonate chemistry in seagrass-associated waters (Ridho and Supriharyono 2018).

Salinity values were recorded between 30-33 ppt, which, although slightly below the optimal range of 33-34 ppt specified by Indonesian Ministry of Environment Number 51 of 2004, remain within the general tolerance threshold for most tropical seagrass species (10-40 ppt; Bongga et al. 2021). While seagrasses possess a high tolerance for salinity fluctuations, prolonged deviation from optimal ranges can cause physiological stress and tissue damage, leading to reduced growth or mortality.

Current velocities ranged from 0.13-0.16 $m \cdot s^{-1}$, with the highest values observed at Stations 3 and 4. These values are considered slow, as currents above 0.7 $m \cdot s^{-1}$ are classified as fast (Kurniawan et al. 2021). The seasonal transition from the west to east monsoon during the sampling period likely contributed to slight variations in current speed. Current velocity influences sediment stability, nutrient transport, and seagrass leaf movement, all of which affect habitat suitability.

The substrate at most stations consisted of sand mixed with coral rubble, except at Station 2 where it was predominantly sandy. Substrate composition is a key factor in seagrass establishment and horizontal spread, as it affects root anchorage, sediment stability, and nutrient retention (Rosalina et al. 2022). The prevalence of coral rubble-sand mixtures at Stations 1, 3, and 4 supports the growth of multiple seagrass species, while the finer sandy substrate at Station 2 may influence species composition and density.

Changes in seagrass distribution

Changes in seagrass distribution between 2022 and 2023 were analyzed using Sentinel-2A satellite imagery acquired on December 18, 2022, and December 23, 2023. The imagery, obtained from the Copernicus SciHub platform, consisted of raw remote sensing data for Band 2 (Blue), Band 3 (Green), and Band 4 (Red). Several processing stages were conducted to extract seagrass distribution patterns. Initially, image compositing was performed using the selected spectral bands, followed by a masking procedure to separate terrestrial and marine areas. Subsequent classification was applied to identify seagrass bed locations.

In the classification process for shallow-water habitats, water column correction is essential to minimize the influence of depth-related light attenuation, which can obscure benthic features. This step involved attenuation correction by selecting Regions of Interest (ROI) at varying depths, enabling more accurate spectral separation of benthic classes. The Lyzenga attenuation coefficient (ki/kj) was calculated to perform water column correction, following the method outlined by Maulana et al. (2018). This correction reduced water depth effects and enhanced the visibility of benthic substrates, allowing for more precise delineation of seagrass beds. The resulting processed imagery produced a distribution map of seagrass beds for the 2022-2023 period, as shown in Figure 7. This map illustrates spatial changes in seagrass coverage and provides a baseline for assessing temporal trends in habitat extent.

Based on the water column correction imagery, certain areas remain imperfectly corrected. In 2022, several points were classified as live coral; however, by 2023, these same points were identified as dead coral. This change may be influenced by water conditions at the time the Sentinel imagery was captured. According to Hafizt and Danoedoro (2015), such discrepancies can occur due to factors affecting the water column, including algae attached to sand or suspended organic matter, both of which can alter light absorption and reflection, thereby influencing spectral penetration to benthic objects. The spatial analysis further indicates that seagrass distribution tends to increase in areas located farther from the shoreline. This pattern may be linked to disturbances within nearshore seagrass ecosystems caused by waste disposal and human activities, which exert a measurable impact on habitat condition. Conversely, offshore areas with calmer waters and minimal anthropogenic disturbance tend to exhibit healthier seagrass cover. The distribution of seagrass on Gili Trawangan Island is presented in Table 3.

Based on the results presented in Table 3, between 2022 and 2023 the distribution of seagrass beds on Gili Trawangan Island decreased by 31 hectares, with a rate of change of 0.31%. According to one respondent, this decline was partly due to intensive tourism activities at the end of 2023, which contributed to physical damage to seagrass habitats. Additionally, during the rainy season, sediment movement and increased freshwater input reduced water quality and disrupted the photosynthetic processes of seagrass, further contributing to the loss of 31 hectares in 2023. This is consistent with the findings of Curry et al. (2020), who noted that changes in light availability, often driven by human activities can impact seagrass health.

Damage to seagrass beds in Indonesia can result from both natural and anthropogenic factors. Chemical factors such as elevated temperatures, altered growth rates, and changes in reproductive patterns can also influence seagrass survival, potentially leading to mortality and degradation of the surrounding aquatic environment. Furthermore, the seagrass ecosystem is under pressure from threats such as shallowing, which increases sedimentation rates, as well as other human-induced disturbances. Changes in the seagrass bed area on Gili Trawangan Island over this two-year period (2022-2023) are illustrated in Figure 8.

Over the two-year period from 2022 to 2023, the widest distribution of seagrass beds on Gili Trawangan Island occurred in 2022, covering an area of 75 ha, compared to 44 ha in 2023. This difference is largely attributed to the dominance of the seagrass species *C. rotundata*, which typically spreads across depths of 3-15 meters (Adi 2015). Hydrodynamic conditions also play an important role in shaping seagrass distribution. The current speed around Gili Trawangan Island ranges from 0.14 to 0.16 m/s. During the west season, when currents are relatively strong, seagrass growth can be hindered, whereas in the east season, when currents slow, seagrass beds tend to flourish. This is consistent with Wahab et al. (2018), who reported that water currents considerably influence seagrass distribution.

The lowest recorded seagrass coverage in the study period was in 2023, at 44 ha. Annual declines in seagrass area are primarily linked to human activities, including improper waste disposal, high-intensity tourist boat traffic, and physical damage from ship anchors, as supported by Fahruddin et al. (2017). One direct ecological consequence of this decline is the reduction in the abundance and diversity of associated marine biota, particularly coral species, which have shown a consistent yearly decrease. Seagrass beds provide critical ecosystem functions, including food provision, shelter, spawning grounds, and nursery habitats for various marine organisms (Wong 2018). In the long term, degradation of the seagrass ecosystem poses distinct socio-economic risks, especially for local fishing communities, as fish populations decline and fishing grounds become more distant.

Table 3. Rate of seagrass distribution decline (%) on Gili Trawangan Island, West Nusa Tenggara Province, Indonesia, between 2022 and 2023, based on Sentinel-2A imagery analysis after water column correction

Year	Seagrass area (Ha)	Area change (Ha)	Rate of change (%)
2022	75	0	0
2023	44	31	0.31

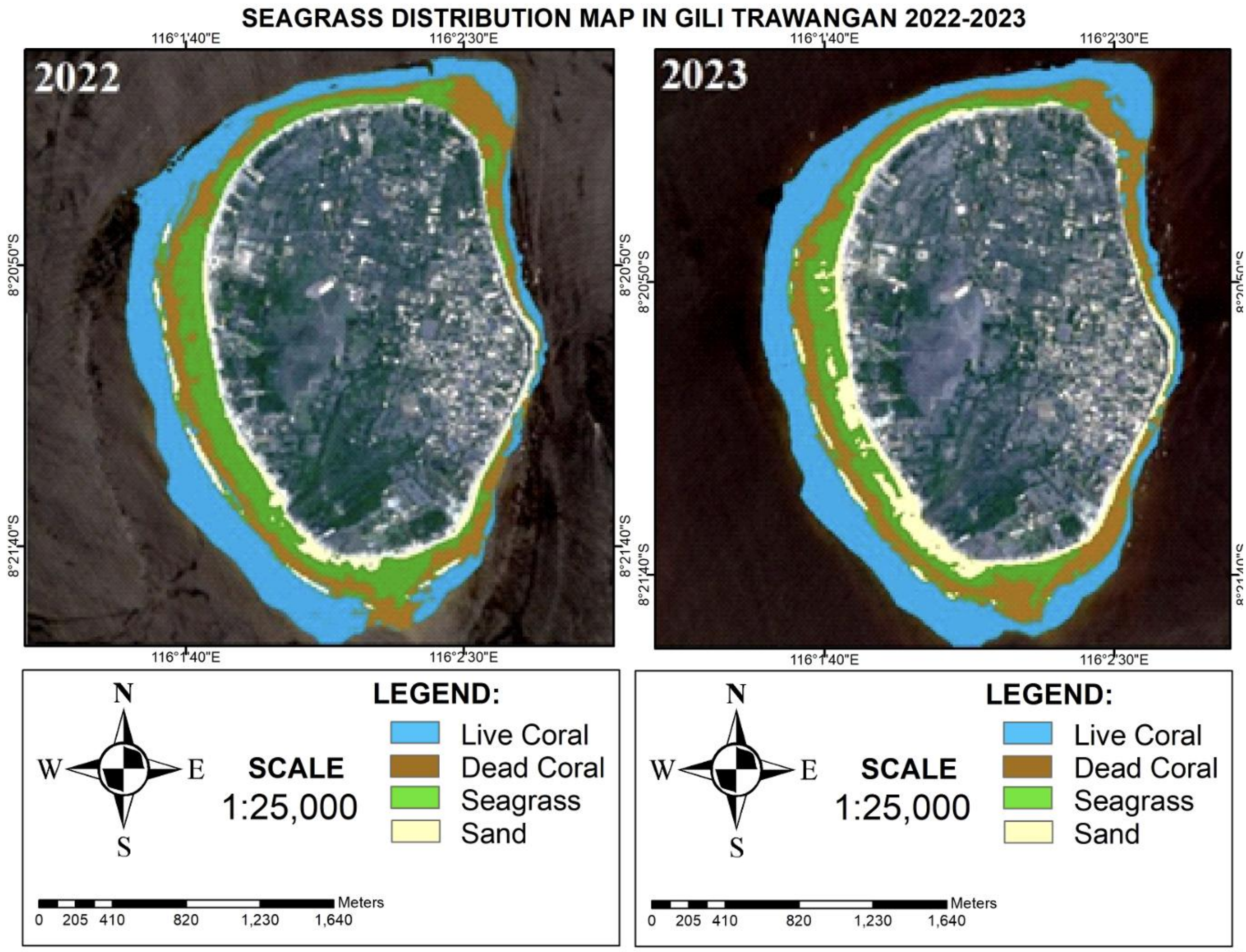

Figure 7. Seagrass distribution map in of Gili Trawangan Island, West Nusa Tenggara Province, Indonesia, for the period of 2022-2023

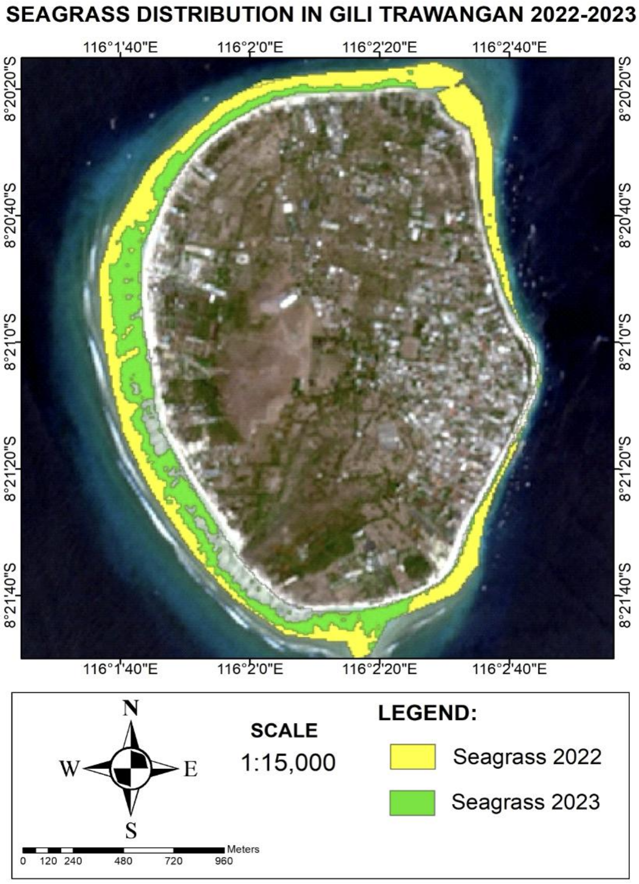

Figure 8. Map showing change in seagrass area in Gili Trawangan Island, West Nusa Tenggara Province, Indonesia, between 2022 and 2023

Seagrass ecosystems are generally under pressure from fishing activities, pier construction, tourism, and other disruptive practices (Vieira et al. 2020; Riniatsih et al. 2023). Such disturbances directly impair seagrass health, which in turn affects the growth and survival of associated marine organisms (Sando et al. 2022). Given that many species rely on seagrass as a primary feeding ground, any reduction in its coverage can have cascading ecological impacts.

Analysis of spatial distribution and temporal changes in seagrass cover using satellite imagery offers valuable insights for marine conservation planning. Areas exhibiting substantial losses should be prioritized for restoration and management. The observed changes are likely driven by sedimentation during the rainy season, high tourism pressure, and potential climate-related stressors such as increased sea surface temperatures. These results highlight the urgent need for spatially informed conservation strategies to safeguard seagrass biodiversity and the ecosystem services it provides.

Field surveys identified three seagrass species in the waters of Gili Trawangan Island: *Cymodocea rotundata*, *T. hemprichii*, and *H. pinifolia*. Across all four sampling stations, *C. rotundata* exhibited the highest density and was dominant, whereas *T. hemprichii* consistently had the lowest density. Spatial analysis revealed a notable decline in total seagrass coverage from 75 ha in 2022 to 44 ha in 2023. This reduction highlights the importance of strengthening conservation measures. Recommendations include implementing routine seagrass monitoring programs that combine remote sensing with field validation, mitigating anthropogenic pressures such as tourism, anchoring, and coastal development, and incorporating higher-resolution technologies such as drone-based imaging to enhance spatial detail and detection accuracy. Furthermore, future research should investigate the ecological consequences of seagrass loss on marine biodiversity and ecosystem functioning to better inform adaptive management strategies.

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