BIODIVERSITAS
Volume 27, Number 2, February 2026
Pages: 9

ISSN: 1412-033X
E-ISSN: 2085-4722
https://doi.org/10.13057/biodiv/d270216

Spatio-temporal distribution of seagrass extent in three zones of Spermonde Archipelago, Indonesia

ST. FIRJATIH WIDHAH[1], ROHANI AMBO-RAPPE[2,3,♥], LUKY ADRIANTO[4,5]
[1]Faculty of Marine Science and Fisheries, Universitas Hasanuddin. Jl. Perintis Kemerdekaan Km. 10, Makassar 90245, South Sulawesi, Indonesia
[2]Marine Science Department, Faculty of Marine Science and Fisheries, Universitas Hasanuddin. Jl. Perintis Kemerdekaan Km. 10, Makassar 90245, South Sulawesi, Indonesia. Tel.: +62-411-586025, ♥email: rohani.amborappe@mar-sci.unhas.ac.id
[3]Seagrass Restoration and Ecosystem Services Research Group, Universitas Hasanuddin. Jl. Perintis Kemerdekaan Km. 10, Makassar 90245, South Sulawesi, Indonesia
[4]Department of Aquatic Resources Management, Faculty of Fisheries and Marine Sciences, Institut Pertanian Bogor. Jl. Agatis, Bogor 16680, West Java, Indonesia
[5]Center for Coastal and Marine Resources Studies, Institut Pertanian Bogor. Jl. Agatis, Bogor 16680, West Java, Indonesia

Manuscript received: 21 September 2025. Revision accepted: 27 February 2026.

Abstract. *Widhah SF, Ambo-Rappe R, Adrianto L. 2026. Spatio-temporal distribution of seagrass extent in three zones of Spermonde Archipelago, Indonesia. Biodiversitas 27 (2): d270216. https://doi.org/10.13057/biodiv/d270216.* Seagrass meadows are vital blue carbon habitats that support biodiversity, fisheries, and coastal defense, but human activities and environmental changes increasingly threaten them. This research examined how seagrass distribution shifted over time and space across Barrang Lompo, Badi, and Langkai Islands in the Spermonde Archipelago, Indonesia, representing inner, middle, and outer zones. Using supervised classification of Sentinel-2 satellite images from 2015 and 2025, validated by field observations, we identified distinct regional patterns of seagrass loss over a decade. Area measurements included 95% confidence intervals, and all observed declines were confirmed by field data. Over ten years, seagrass cover shrank by 12.53 hectares (30.69%) in Barrang Lompo, 3.91 hectares (56.02%) in Badi, and 12.23 hectares (26.86%) in Langkai. Major losses were noted in Barrang Lompo and Badi due to dense populations, intensive fishing, land-use change, and pollution, while oceanographic factors like strong currents, sediment buildup, and variable water quality mainly drove Langkai's decline. These spatial patterns demonstrate the combined impacts of human stressors and environmental factors on seagrass decline and underscore the necessity for targeted conservation efforts, water quality improvements, and zone-specific fisheries management to protect blue carbon functions and ecosystem resilience in the Spermonde Archipelago.

Keywords: Blue Carbon, coastal management, conservation strategies, marine ecosystem, small island

INTRODUCTION

Seagrasses are true flowering plants that have successfully adapted to marine environments, comprising about 60 species worldwide that are grouped into five families: Hydrocharitaceae, Potamogetonaceae, Cymodoceaceae, Zosteraceae, and Ruppiaceae (den Hartog 1970). They are widely distributed in shallow coastal waters, estuaries, and lagoons, where they act as important foundation species that support biodiversity and ecosystem functioning (McKenzie et al. 2020). Seagrass meadows are highly productive ecosystems, contributing significantly to primary production in coastal zones and providing multiple ecological and socioeconomic benefits, including supporting fisheries, protecting shorelines from erosion, stabilizing sediments, maintaining water quality, and storing carbon that contributes to climate change mitigation (Ambo-Rappe et al. 2019; Ambo-Rappe 2020). Despite these important roles, seagrasses often receive less attention compared to coral reefs and mangroves, which has contributed to their global decline being less documented and less visible in conservation policy. Research attention among coastal ecosystems is uneven: coral reefs dominate with ~60% of publications, mangroves receive moderate focus (≈11-14%), while seagrasses remain the least studied and recognized, despite a similar publication share, with far lower media coverage and public awareness (Duarte et al. 2008).

Indonesia, located at the center of marine biodiversity, hosts some of the world's largest seagrass meadows. Seventeen species have been documented within its waters, including the recently described *Halophila major* (Zoll.) Miq. and *Ruppia brevipedunculata* Shuo Yu & Hartog (Kurniawan et al. 2020; Kurniawan et al. 2024; Salim et al. 2024). The estimated area of Indonesian seagrass meadows is 660.000 ha (Ministry of Marine Affairs and Fisheries 2025). Nevertheless, this estimate likely underrepresents the actual extent, and Indonesia may potentially possess the largest seagrass habitat of any nation (Unsworth et al. 2018). Regional assessments further indicate that between 30% and 40% of Indonesia's seagrass meadows have already been lost due to human-induced pressures, including overexploitation, eutrophication, destructive fishing practices, coastal reclamation, and climate-related stressors (Muqorrabin et al. 2024). These losses pose a direct threat to essential ecosystem services, thereby endangering fisheries productivity, carbon sequestration, and the livelihoods of coastal communities that rely heavily on seagrass meadows.

South Sulawesi has seagrass beds covering 91,699 hectares. One of the areas in South Sulawesi where seagrass can be found is the Spermonde Archipelago. The Spermonde Archipelago, located off the coast of South Sulawesi, is one of Indonesia's most seagrass-rich areas, consisting of over a hundred small coral islands and reef flats where seagrass is frequently found. At least 11 species of seagrass have been reported from this region (Ambo-Rappe 2014), highlighting its ecological significance. Besides their ecological roles, seagrass meadows in Spermonde provide vital livelihoods, supporting artisanal fisheries and coastal protection for local communities. Research by Mashoreng et al. (2020) states that there is a decrease in the extent of seagrass in the Spermonde Archipelago, which impacts carbon uptake. However, research on seagrass distribution within the archipelago remains scarce. Despite its importance, research on seagrass distribution in Spermonde remains limited and fragmented. Effective monitoring of seagrass ecosystems requires a combination of field-based and remote-sensing techniques. Satellite imagery is useful for efficiently assessing water conditions in shallow waters (Nur and Nurdjaman 2025). Previous mapping research has mostly concentrated on individual sites, such as Bontosua (Thalib 2017), Barrang Caddi (Kartika 2019), Lae-lae and Bonetambung (Yushra et al. 2020) and Kodingareng Lompo (Rais 2021). While these studies offer valuable insights, they lack a comprehensive spatio-temporal perspective across the broader archipelago. Furthermore, bibliometric studies indicate that the Spermonde Islands have become a global centre for seagrass ecosystem research, emphasising biodiversity, ecosystem services, and blue carbon (Widhah et al. 2025). This trend underscores Spermonde's scientific importance and the need for systematic studies on long-term changes in seagrass distribution to support sustainable management.

Another significant gap is the limited use of remote sensing in Spermonde, primarily focusing on coral reefs and mangroves, with less attention to systematic monitoring of seagrass dynamics (Mashoreng et al. 2018; Veettil et al. 2020). This study aims to fill this gap through a spatio-temporal analysis of seagrass distribution across three representative zones of the Spermonde Archipelago, combining satellite remote sensing with field validation. By mapping seagrass extent and tracking changes over time, it strives to offer new insights into habitat dynamics, resilience, and degradation patterns. The findings are expected to support ecosystem-based management strategies, bolster biodiversity conservation, and improve ecosystem services like fisheries productivity, coastal protection, and blue carbon storage. Ultimately, these efforts will promote the sustainability of coastal communities in one of Indonesia's most ecologically and economically vital marine regions. Accordingly, this study explicitly aims to quantify decadal changes in seagrass extent across inner-, middle-, and outer-zone islands and to relate these changes to zone-specific anthropogenic and environmental stressors. We hypothesize that seagrass losses will be greatest in densely populated inner zones due to higher anthropogenic pressures, whereas outer-zone islands will exhibit smaller yet significant declines primarily driven by oceanographic conditions rather than direct anthropogenic disturbance.

MATERIALS AND METHODS

Study area

This research was carried out from July to August 2024, in the Spermonde Islands, Pangkajene District, and the waters of South Sulawesi Province, Indonesia. Field data collection focused on three islands: Barrang Lompo Island, Badi Island, and Langkai Island. A map of the study area is shown in Figure 1.

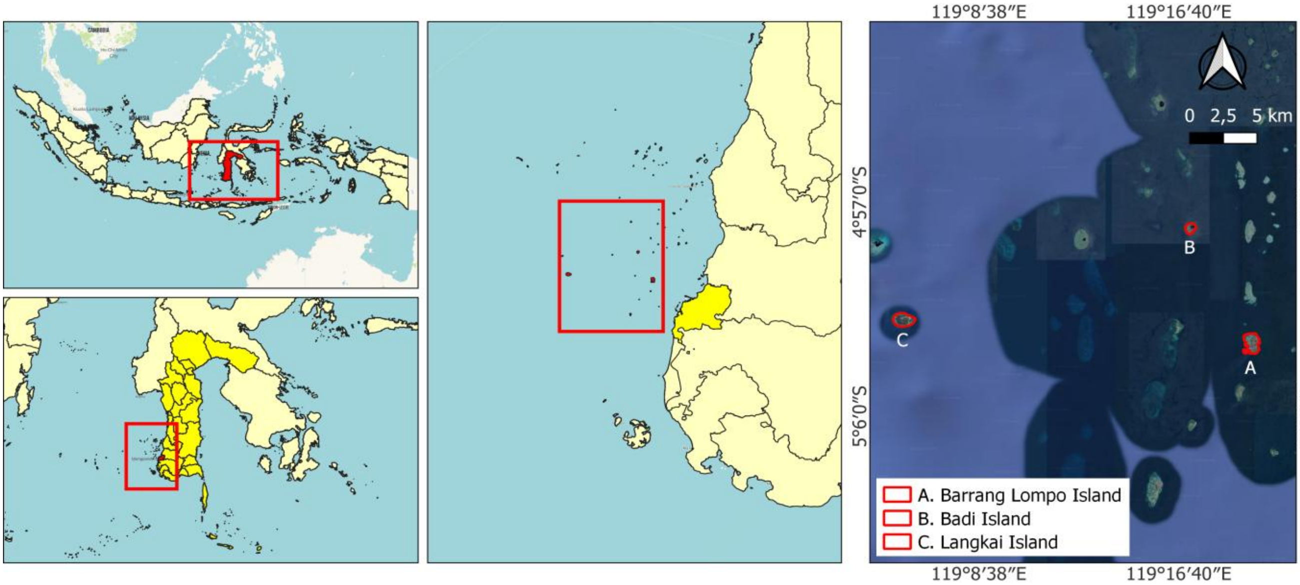


Figure 1. Map of the research sites in in South Sulawesi Province, Indonesia. A. Barrang Lompo Island (119.327360°, -5.050339°), B. Badi Island (119.287664°, -4.968726°), C. Langkai Island (119.091471°, -5.030949°)

Types and resources of data

This study utilized both primary and secondary data. Primary data were gathered through direct field observations, such as seagrass data collection. Secondary data were sourced from publicly accessible satellite databases via remote sensing imagery.

Data collection methods

Two primary methods were utilized for data collection; the first involved direct field observations to document seagrass distribution and associated environmental parameters. The second encompassed remote sensing data processing to map and analyze seagrass coverage. The overall data collection procedure is depicted in Figure 2.

Field data retrieval

Seagrass surveys in the Spermonde Archipelago were conducted around Barrang Lompo Island, Badi Island, and Langkai Island using a quadrat-transect (straight-line transect) method adapted from the Seagrass-Watch protocol and CORMEP-LIPI (National Research and Innovation Agency of Indonesia) guidelines. At each island, transects were established following shoreline contours and the spatial distribution of accessible seagrass meadows. Transect lengths ranged from 70 to 340 m, depending on local geomorphological characteristics and meadow extent.

To standardize sampling effort across transects of varying lengths, each transect was uniformly divided into 11 equal segments (10% intervals), resulting in 11 fixed quadrat positions per transect. At each position, a 50 × 50 cm quadrat was placed to visually estimate seagrass percent cover using the internal subdivisions of the quadrat frame. Substrate type was recorded simultaneously and classified as mud, sand, or rubble. The map of the study area is shown in Figure 1.

Field sampling was conducted during low tide, specifically within the lowest tidal window, to ensure maximum seagrass exposure, consistent observation conditions, and observer safety. Prior to data collection, standardized field sheets were completed to document observer identity, island code, transect number, date, time, and tidal conditions. The starting point of each transect was marked with an iron stake, and its geographic coordinates were recorded using a handheld GPS. Each transect was completed only after all 11 quadrat positions had been surveyed, and the endpoint of each transect was subsequently marked and georeferenced.

In addition to biological observations, environmental parameters were measured in situ at each transect to characterize local habitat conditions. Water temperature (°C) and salinity ($^{o}/_{oo}$) were measured using a handheld multiparameter instrument, while pH was recorded using a portable pH meter. Water transparency was measured using a Secchi disk. All measurements were conducted during the same tidal conditions as the seagrass sampling to ensure consistency across sites.

Seagrass species were identified in situ based on leaf morphology, rhizome characteristics, and growth form, following Seagrass-Watch identification keys and CORMEP-LIPI taxonomic references. To ensure data quality, all observers received prior training, and inter-observer consistency checks were conducted at selected quadrats. Any ambiguous species identifications or percent cover estimates were discussed and resolved jointly in the field.

Data processing

The processing of remote sensing data in this study followed a systematic sequence of procedures designed to ensure high analytical accuracy and reliability in benthic habitat interpretation. The workflow began with the acquisition of satellite imagery, specifically Sentinel-2A Level-1C data obtained from the Copernicus Open Access Hub. Image selection considered cloud-cover levels, as scenes with minimal cloud interference provide optimal conditions for precise spectral analysis.

The next phase involved atmospheric correction, carried out using ArcGIS to adjust for atmospheric scattering and surface-reflection effects that often distort radiometric values, especially in coastal and shallow-water environments. This correction step ensures that spectral information more accurately reflects true benthic conditions rather than atmospheric anomalies.

Following atmospheric refinement, spectral band compositing was performed by combining selected multispectral bands to enhance spectral separability and improve the visual interpretability of coastal features. The imagery was then clipped to the defined study area to streamline analytical focus, and masking was applied to exclude terrestrial pixels, allowing the subsequent analysis to concentrate solely on the marine domain.

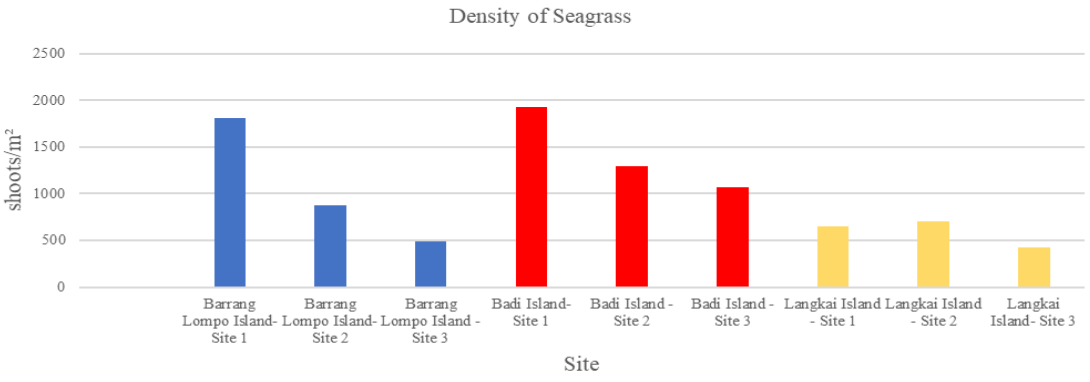


Figure 2. Density of seagrass in Barrang Lompo, Badi, and Langkai Islands in South Sulawesi Province, Indonesia

To further improve the discrimination of benthic substrates, the Lyzenga method was applied. This radiative-transfer-based algorithm compensates for water-column attenuation, thereby enhancing the spectral contrast between different bottom types such as sandy substrates, coral formations, and seagrass meadows. The method utilizes attenuation-adjusted band ratios, facilitating clearer detection of submerged vegetation and other benthic features.

The final stage consisted of supervised image classification. Representative training sites were established through in situ surveys, during which coordinates of key benthic classes were recorded. These ground-truth observations served as reference signatures for classifying satellite pixels. Incorporating field-based information substantially improved thematic accuracy, ensuring that the resulting habitat maps provide a valid and ecologically meaningful depiction of benthic conditions across the study area.

Data analysis

Data analysis in this study focused on processing seagrass field data and interpreting remotely sensed imagery. Seagrass density was measured to determine the ecological condition of the seagrass meadow at each sampling station, while seagrass cover was calculated as the total percentage of substrate covered by all seagrass species combined. These two parameters served as the primary indicators for describing overall seagrass condition and spatial distribution patterns within the study area.

For the remote sensing component, the Lyzenga Algorithm was applied to extract benthic substrate information based on the reflectance values of the blue band (Band 2) and green band (Band 3). The initial step involved statistical analysis to derive the coefficient *a*, computed using the variance and covariance of the reflectance values from the two spectral bands. All variance and covariance calculations were performed using Microsoft Excel.

Spatial changes in seagrass distribution between 2015 and 2025 were quantified using a post-classification comparison approach. Independently classified seagrass maps for each year were overlaid to identify areas of persistence, loss, and gain. Seagrass area was calculated for each island and year, and changes were derived by subtracting the earlier map from the later map on a class-by-class basis. This method minimizes radiometric inconsistencies between acquisition dates and allows direct interpretation of categorical changes in seagrass extent.

The coefficient *a* was then used to determine the band attenuation ratio $\frac{k_i}{k_j}$, which was subsequently applied to the Lyzenga transformation according to the following equation:

$$Y = \ln(L_i) - \frac{k_i}{k_j}\ln(L_j)$$

Where: Y= the benthic substrate extraction result, L_i= Reflectance of Band 2 (blue), L_j= Reflectance of Band 3 (green), $\frac{k_i}{k_j}$= Attenuation coefficient ratio between the bands, and ln = Natural logarithm.

This transformation enhances the discrimination of benthic substrate types, enabling clearer identification of seagrass-covered areas within the satellite imagery. In addition to image-based analysis, statistical analysis was performed using SPSS, employing multiple linear regression to examine the influence of environmental variables on seagrass ecological parameters. The regression model evaluated how factors such as water clarity, nutrient concentrations, salinity, and depth contributed to variations in seagrass density across sampling stations. Prior to regression, standard diagnostic tests-normality, multicollinearity, and heteroscedasticity-were conducted to ensure the validity of the model. The results of this analysis provided a quantitative understanding of the key environmental drivers shaping seagrass condition in the study area.

RESULTS AND DISCUSSION

Species of seagrass

During the field survey, we identified eight different seagrass species, including *Enhalus acoroides* (L.f.) Royle, *Thalassia hemprichii* (Ehrenb.) Asch., *Cymodocea rotundata* Asch. & Schweinf., *Oceana serrulata* (R.Br.) Byng & Christenh., *Halophila ovalis* (R.Br.) Hook.f., *Halodule pinifolia* (Miki) Hartog, *Halodule uninervis* (Forssk.) Boiss., and *Syringodium isoetifolium* (Asch.) Dandy. Barrang Lompo Island recorded eight species, Badi Island six species, and Langkai Island five species.

The seagrass species composition across the three research islands varies distinctly, based on direct in situ identification during field surveys. Barrang Lompo has the greatest diversity with eight species, followed by Badi with six, and Langkai with five. This study describes the variations in species richness among the islands to highlight the spatial differences in seagrass communities, but it does not include direct measurement or analysis of the specific habitat conditions or ecosystem features that may explain these differences. Barrang Lompo has the highest number of species, with eight species, while Badi has recorded six species, and Langkai has five species. This difference in the number of species reflects variations in habitat conditions and local ecosystem characteristics that are not directly described in this study. The presence of species such as *E. acoroides, T. hemprichii,* and *C. rotundata*, which appear consistently in almost all locations, indicates that these three species are the main components of the seagrass community in the research area.

Table 1. Distribution of seagrass species in Barrang Lompo, Badi and Langkai Islands in South Sulawesi Province, Indonesia

Island name	EA	TH	CR	CS	HU	HO	SI	HP
Barrang Lompo Island	+	+	+	+	+	+	+	+
Badi Island	+	+	+	-	+	+	+	-
Langkai Island	+	+	+	-	+	-	+	-

Note: Ea: *Enhalus acoroides*, Th: *Thalassia hemprichii*, Cr: *Cymodocea rotundata*, Cs: *Oceana serrulata*, Si: *Syringodium isoetifolium*, Hu: *Halodule uninervis*, Ho: *Halophila ovalis*, Hp: *Halodule pinifolia*

The distribution of species across the islands also indicates variation in species tolerance to microenvironmental characteristics (Table 1). Studies show that local abiotic factors, including sediment type, nutrient status, water temperature, and salinity, influence the spatial patterns of seagrass species distribution. For example, in tropical Indo-Pacific regions, distinct environmental niches have been observed even within a single wide-ranging species, suggesting local adaptations to environmental heterogeneity (Hu et al. 2021). Similarly, variations in sediment and nutrient input in habitats can influence the microbial communities linked to different seagrass species, highlighting how microenvironmental factors affect species composition in seagrass beds (Deng et al. 2024). This confirms that the seagrass communities on the three islands are heterogeneous, comprising species with different habitat preferences. Multispecies seagrass beds (mixed stands of more than two species) occur widely in the tropics, including Southeast Asia and the Caribbean (Duarte 2000; Short et al. 2011).

Barrang Lompo Island showed the highest seagrass diversity compared to Badi and Langkai, with eight species found in its inner zone. These include *E. acoroides, T. hemprichii, C. rotundata, C. serrulata, S. isoetifolium, H. ovalis, H. uninervis*, and *H. pinifolia*. The meadows mainly consist of *E. acoroides* and *T. hemprichii*, two dominant species known for tall shoots, large biomass, and high tolerance to environmental stresses (Risandi et al. 2023). The high species richness in Barrang Lompo is mainly due to sheltered conditions formed by surrounding reef structures, which reduce wave energy and create a calm hydrodynamic environment. Coupled with fine sandy and rubble substrates, these conditions support both strong and delicate species, such as Halodule and Halophila. Previous research by Supriadi et al. (2012) found eight seagrass species on Barrang Lompo Island. This aligns with Hernawan et al. (2017), who reported that sheltered Indonesian coastal lagoons usually have higher seagrass diversity because of stable water movement and less physical stress. Additionally, seagrass beds help slow wave energy and current speed, further aiding their ability to expand and maintain high species numbers (Ondiviela et al. 2014).

Badi Island hosts six seagrass species, namely *E. acoroides*, *T. hemprichii*, *C. rotundata*, *S. isoetifolium*, *H. ovalis*, and *H. uninervis*. Situated in the central Spermonde Islands, Badi is more exposed to stronger currents and waves than the inner islands, creating hydrodynamic stress that affects seagrass growth. Dewanto (2022) reported that higher sea wind speeds contribute to reduced seagrass density and coverage on the island, while additional pressures from human activities such as coastal development and fishing further exacerbate this decline. Compared to Barrang Lompo, Badi experiences more intense hydrodynamic activity, which creates a selective habitat favoring medium to large species while limiting the presence of smaller, fragile taxa due to substrate instability.

Langkai Island supports five seagrass species, *E. acoroides*, *T. hemprichii*, *C. rotundata*, *S. isoetifolium*, and *H. uninervis*, representing the lowest diversity among the three islands studied. Situated in the outer Spermonde zone and directly bordering the Flores Sea, Langkai is strongly influenced by open-ocean conditions, including high waves, strong currents, and steep depth gradients. These oceanographic stresses create selective habitats that favour resilient species, with *E. acoroides* and *T. hemprichii* dominating due to their tall morphology, large biomass, and high resistance to environmental pressure (Risandi et al. 2023). In addition to natural drivers, anthropogenic disturbances such as destructive fishing, anchoring, and waste disposal have further degraded the ecosystem (Jompa et al. 2005), limiting the survival of smaller and more fragile species. This dominance of robust taxa in high-energy settings aligns with Waycott et al. (2009), who emphasized that large-leaved seagrasses are better adapted to exposed reef environments. Overall, the seagrass distribution in Langkai reflects a clear zonation gradient, where inner islands sustain higher diversity, middle zones moderate richness, and outer zones have the lowest species composition.

Environmental conditions in the inner zone provide sheltered habitats that support a wide variety of seagrass species, while outer zones are exposed to high hydrodynamic energy that restricts the establishment of smaller or fragile taxa, leaving only large and resilient species (Kilminster et al. 2015). These zonal differences in species richness emphasize the critical role of habitat heterogeneity in maintaining seagrass diversity across the Spermonde Archipelago. Barrang Lompo, with the highest diversity, could serve as a reference site for monitoring ecosystem health, whereas management efforts in Badi should prioritize reducing anthropogenic pressures to prevent further biodiversity decline. Choesin et al. (2024) showed that seagrass ecological quality indices are strongly influenced by both habitat conditions and human activities, underscoring the need for integrated assessment. Combining these indices with remote sensing-based monitoring, as applied in this study, offers a valuable approach for strengthening long-term conservation and management strategies in the region.

Table 2. Oceanographic conditions for seagrass in Barrang Lompo Island, Badi Island, and Langkai Island in South Sulawesi Province, Indonesia

Parameter	**Unit**	**Island**			**Quality standards (Ministry of Environment 2004)**
		Barrang Lompo Island	**Badi Island**	**Langkai Island**	
Temperature	⁰C	30.7±0.7	30.2±0.8	32.5±0.8	28 - 32
Salinity	⁰/₀₀	33.6±0.7	30.3±0.7	32±0.7	33 - 34
Clarity (visibility)	%	100±0	100±0	100±0	-
Nitrate	Mg/l	0.89±0.26	0.91±0.26	0.31±0.02	0.008
Phosphate	Mg/l	0.26±0.02	0.27±0.05	0.05±0.01	0.015
Substrate		Sand	Sand-Rubble	Sand	-

Oceanographic condition

Table 2 indicates that environmental factors significantly influence the distribution, growth, and development of seagrass species in marine environments. Water temperatures across sites ranged from 30.2±0.8-32.5±0.8°C, salinity ranged from 30.3±0.7-33.6±0.7‰, and clarity reached 100%. The dominant substrate was sand, with some coral rubble in certain areas listed in the table below.

The analysis of oceanographic parameters across the three islands in the Spermonde Archipelago reveals notable environmental differences that could impact seagrass density. Overall, water temperature stayed within the optimal range specified in the Ministry of Environment Decree (KepMen LH No. 51/2004), which is 28-32°C, except at Langkai Island, where the temperature slightly surpassed the upper limit (32.5°C). Higher temperatures above 32°C may cause thermal stress in seagrasses (Zhang 2016). Exposure to elevated temperatures can promote microbial reduction reactions, leading to hypoxia in the substrate and the formation of sulfide, which negatively affects the survival and growth of seagrass. This indicates that the temperature parameter shows a significant value of $p = 0.010$, indicating a real difference between islands, supported by Pearson correlation results, where salinity has a significant negative correlation with seagrass density ($r = -0.589$; $p = 0.048$), suggesting that an increase in salinity generally correlates with a decrease in seagrass density.

Salinity at the research site varies from 30.3 to 33.6‰. These values are mostly just below the standard quality threshold of 33-34‰, particularly on Badi Island and Barrang Lompo. Shen et al. (2022) reported that seagrass mortality rates at salinity levels from 25 to 35 ppt do not exceed 10%, and all plants grow normally with green leaves, although drastic changes can affect seagrass growth and distribution. Salinity shows a very weak and insignificant positive relationship with seagrass density ($r = 0.116$; $p = 0.384$). These results indicate that the variation in salinity at the research location remains within the physiological tolerance range of seagrass, thus not having a significant effect on seagrass density. Therefore, salinity is not the main limiting factor in the environmental conditions of this study.

The clarity remains consistently optimal at 100% across all sites. Water clarity was measured during low tide, which significantly affects how we interpret these values. Higher brightness allows better light penetration to the seabed, critical for seagrass photosynthesis. Moreover, increased brightness indicates low sedimentation and turbidity, which helps seagrass growth. This supports Duarte's (1991) assertion that light availability is the key limiting factor for healthy seagrass ecosystems.

The nutrient parameters significantly exceed the quality standards established by the Minister of Environment, particularly nitrate (standard 0.008 mg/L) and phosphate (0.015 mg/L). At all sampling sites, the highest nitrate level was recorded on Barrang Lompo Island at 0.89 mg/L, while the highest phosphate level was on Badi Island at 0.27 mg/L. Although values on other islands were lower, they still indicate eutrophication pressure. Nutrient concentrations also vary notably across locations, with nitrate showing a p-value of 0.022 and phosphate a more significant p-value of less than 0.001, suggesting big spatial differences. Regression analysis confirms that higher levels of these nutrients are positively associated with declining seagrass density. Correlation analysis reveals significant positive relationships: nitrate ($r = 0.588$; $p = 0.048$) and phosphate ($r = 0.593$; $p = 0.046$). This could be due to two reasons: (i) seagrass acts as a biofilter, absorbing more nutrients in denser areas, or (ii) nutrient-rich sites are near human activity zones that contribute runoff, which still retain dense seagrass coverage. According to Murphy et al. (2021), initially, nutrient increases boost seagrass productivity, but over time, they lead to eutrophication, epiphytic algae growth, and a reduction in seagrass density.

The substrate conditions on the three islands are dominated by sand and coral rubble, which are ideal substrates for seagrass species in tropical waters. Sandy substrates facilitate root establishment and rhizome extension, as well as support sediment stability. According to Randayani et al. (2019), substrates are one of the important factors that determine the distribution and success of seagrass growth.

Hydrodynamic conditions are crucial in determining seagrass distribution and sediment features in the Spermonde Islands. During the November-March monsoon, strong hydrodynamic energy results from the interaction between seasonal winds and wave energy from the Pacific Ocean, which significantly affects the region's fringing reef systems (Cleary et al. 2005; Ambo-Rappe 2022). This period also sees increased water circulation driven by the Indonesian Throughflow (ITF), a key global current transporting warm Pacific waters through the Makassar Strait toward the Indian Ocean. In the Spermonde Archipelago, the ITF combines with monsoonal winds, tidal movements, and reef morphology, creating distinct hydrodynamic regimes across the inner, middle, and outer island zones. The Indonesian Throughflow (ITF) is a global current system that transfers warm water from the Pacific Ocean to the Indian Ocean through Indonesian waters, including the Makassar Strait (Feng et al. 2018; Risandi et. al. 2023).

The inner islands, closer to the mainland, benefit from calmer conditions, lower wave activity, and higher nutrient levels, supporting dense, thriving seagrass meadows. The middle islands experience moderate influence from the ITF, where a balance between current strength and sediment movement creates favorable conditions for intermediate seagrass development. Conversely, the outer islands are subjected to stronger ITF currents and higher waves, which increase hydrodynamic stress and result in sparser seagrass coverage (Rahayu et al. 2019).

Sedimentological studies show that sediments across the Spermonde Archipelago mainly consist of medium- to coarse-grained sands, primarily made up of coral and coralline algae fragments. Differences in sediment types between the exposed outer shelf islands and the sheltered inner shelf islands highlight active sediment transport processes influenced by local water dynamics and reef formations (Janßen et al. 2017).

Hydrodynamic processes shape the variation of organic carbon stocks in seagrass sediments. These stocks are influenced by factors such as the inshore-offshore gradient, sediment redistribution caused by currents, and nutrient dynamics, all of which affect seagrass productivity and the accumulation of organic carbon in sediments (Rahayu et al. 2019).

The combined effects of monsoon winds, the Indonesian Throughflow, and reef morphology create a clear environmental gradient across the Spermonde Islands. This gradient impacts seagrass density, species diversity, sediment characteristics, and the potential for carbon storage within ecosystems. Protected inner islands host dense seagrass beds, while the exposed outer islands experience harsher conditions that limit seagrass growth (Rahayu et al. 2019). Although water clarity and suitable substrates are generally favorable, elevated nutrient levels at the sites suggest ongoing eutrophication, which could threaten the long-term health of these seagrass ecosystems. The strong correlation between environmental factors and seagrass density indicates that local oceanographic conditions-particularly nutrient levels and salinity-are crucial in shaping ecosystem dynamics in the Spermonde Islands.

Accuracy test of seagrass mapping and implications for change analysis

The accuracy assessment confirms that the observed spatial-temporal trends are supported by highly reliable classification results. Overall accuracy values ranged from 91.88% to 96.25% across the study sites, indicating that the majority of validation samples were correctly classified. These high accuracy levels demonstrate the robustness of the classification approach in distinguishing seagrass from other benthic habitats in the Spermonde Archipelago.

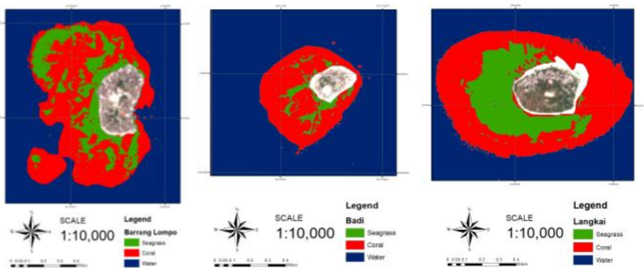
Furthermore, Kappa coefficients ranging from 0.89 to 0.95 indicate strong to near-perfect agreement between the classified maps and the reference data, after adjusting for chance agreement. The consistently high Kappa values confirm that the classification performance reflects genuine discriminatory capability rather than random coincidence. Consequently, the detected declines in seagrass extent can be interpreted with high confidence, providing a solid foundation for assessing ecosystem change and informing management and conservation strategies.

Area of seagrass

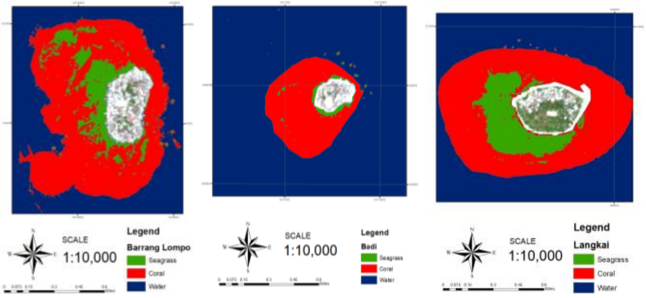
Based on the outcomes of image classification and spatial analysis, the area of seagrass at the three research sites was determined (Figure 3). Seagrass meadows across the Spermonde Islands exhibited a steady decline from 2015 to 2025, signaling mounting stress on these ecosystems throughout the archipelago. While every island faced reductions, the extent of the decline varied in absolute size and percentage, highlighting differences in local environmental factors, island shapes, and human activities.

Figure 4 shows that the largest absolute reduction in seagrass area occurred on Barrang Lompo Island, where it decreased by 12.53 ha, from 40.82 ha in 2015 to 28.29 ha in 2025. Langkai Island also saw a similar decline of 12.23 ha, with seagrass coverage dropping from 45.54 ha to 33.31 ha over the same period. Meanwhile, Badi Island experienced a smaller loss of 3.91 ha, decreasing from 6.97 ha to 3.07 ha.

Badi Island saw the most severe decline in seagrass, losing about 56.02% of its extent when measured proportionally (Table 3). Its small initial seagrass meadow area makes it more vulnerable, so even minor disturbances cause significant proportional losses. The dominance of coral reef substrates limits sediment stability, making seagrass establishment more sensitive to physical disturbances (Jompa et al. 2005). These natural challenges are worsened by human activities like fishing, destructive gear use, and increased household waste. Nutrient pollution and higher turbidity from domestic waste decrease water clarity and light, hindering seagrass photosynthesis, growth, and long-term survival.



Extend of the area of seagrass in 2015



Extent of the area of seagrass in 2025

Figure 3. The extent of the area of seagrass in South Sulawesi Province, Indonesia: Barrang Lompo Island, Badi Island, and Langkai Island in 2015-2025

Table 3. Percentage of seagrass loss in Barrang Lompo, Badi Island, and Langkai Islands in South Sulawesi Province, Indonesia

Island	2015 (HA)	2025 (HA)	Δ HA	%Decline	95% CI extent 2025
Barrang lompo	40.82	28.30	12.53	30.69%	22.41-28.29
Badi	6.97	3.07	3.91	56.02%	2.29-3.04
Langkai	45.54	33.31	12.23	26.86%	28.13-33.31

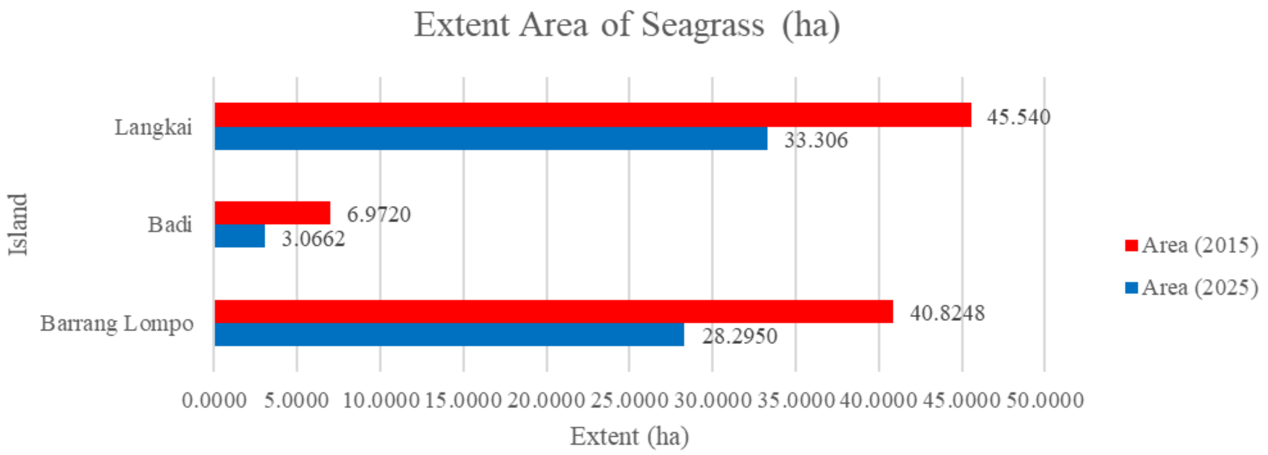


Figure 4. Extent of the area of seagrass in Barrang Lompo Island, Badi Island, and Langkai Island in South Sulawesi Province, Indonesia

Barrang Lompo Island experienced an intermediate decline of about 30.69% (Table 3). As a highly populated island, its seagrass ecosystem is greatly affected by ongoing human activities, including household waste disposal, destructive fishing methods like bombs and poisons, coastal reclamation, and frequent physical disturbances from boat anchoring. Seasonal changes, especially the decrease during the dry season (Selamat et al. 2025), add to these pressures. Its close proximity to Makassar City also subjects the island to external urban impacts, such as pollution and increased resource extraction. This aligns with previous research indicating that higher population density correlates with seagrass decline in small island settings (Mashoreng et al. 2021).

Langkai Island experienced the smallest proportional decline at 26.86% (Table 3), maintaining the largest seagrass area throughout the study. As an outer island, Langkai is mainly affected by open-ocean hydrodynamics, including strong currents, waves, and sediment transport, which influence seagrass distribution on exposed reef flats composed of carbonate sediments. Although human activities like unsustainable resource exploitation and nutrient runoffs from local settlements, alongside natural upwelling (La Nafie 2016), contribute to seagrass loss, the island's lower population density compared to inner islands probably explains why Langkai still has the greatest remaining seagrass coverage in the Spermonde Archipelago.

In conclusion, the decline in seagrass coverage across the Spermonde Islands results from the interaction between anthropogenic pressures and natural oceanographic processes. Destructive fishing practices, pollution, coastal development, and unsustainable resource extraction represent the dominant human-induced stressors, while hydrodynamic forces and sediment dynamics act as additional natural constraints. This pattern aligns with McKenzie et al. (2020), who emphasized that tropical seagrass ecosystems are highly vulnerable to multiple, overlapping stressors that operate simultaneously across spatial scales. Continued seagrass loss poses serious implications for blue carbon storage, fisheries nursery functions, and the livelihoods of coastal communities that depend on these ecosystems.

ACKNOWLEDGEMENTS

The authors would like to express their deepest gratitude to Dr. Muhammad Banda Selamat, S.T., M.Si., for his constructive suggestions on the manuscript. This research was supported by the PMDSU (Pendidikan Magister Menuju Doktor untuk Sarjana Unggul) Scholarship from the Ministry of Research and Technology of Higher Education of Indonesia, Seagrass Restoration and Ecosystem Services Thematic Research Group Universitas Hasanuddin Grant, and Global Green Growth Institute.

REFERENCES

Ambo-Rappe R, La Nafie YA, Marimba AA, Cullen-Unsworth LC, Unsworth RK. 2019. Perspectives on seagrass ecosystem services from a coastal community. IOP Conf Ser Earth Environ Sci 370: 012022. https://doi.org/10.1088/1755-1315/370/1/012022.

Ambo-Rappe R. 2014. Developing a methodology of bioindication of human-induced effects using seagrass morphological variation in Spermonde Archipelago, South Sulawesi, Indonesia. Mar Pollut Bull 86 (1-2): 298-303. https://doi.org/10.1016/j.marpolbul.2014.07.002.

Ambo-Rappe R. 2020. Seagrass meadows for fisheries in Indonesia: A preliminary study. IOP Conf Ser Earth Environ Sci 564: 012017. https://doi.org/10.1088/1755-1315/564/1/012017.

Ambo-Rappe R. 2022. The success of seagrass restoration using *Enhalus acoroides* seeds is correlated with substrate and hydrodynamic conditions. J Environ Manag 310: 114692. https://doi.org/10.1016/j.jenvman.2022.114692.

Choesin DN, Gouw AD, Pitriana P. 2024. Assessment of ecosystem health and carbon stocks in the seagrass meadows of Mengiat Beach, Bali, Indonesia. J Mar Sci 29 (4): 481-494. https://doi.org/10.14710/ik.ijms.29.4.481-494.

Cleary DF, Becking LE, de Voogd NJ, Renema W, de Beer M, van Soest RW, Hoeksema BW. 2005. Variation in the diversity and composition of benthic taxa as a function of distance offshore, depth, and exposure in the Spermonde Archipelago, Indonesia. Estuar Coast Shelf Sci 65 (3): 557-570. https://doi.org/10.1016/j.ecss.2005.06.025.

den Hartog C. 1970. The Seagrasses of the World. North Polland Publishing Co., Amsterdam.

Deng W, Chen S, Chen S, Xing B, Chan Z, Zhang Y, Chen B, Chen G. 2024. Impacts of eutrophication on microbial community structure in sediment, seawater, and phyllosphere of seagrass ecosystems. Frontier Microbiol 15: 1449545. https://doi.org/10.3389/fmicb.2024.1449545.

Dewanto RO. 2022. The Relationship Between Wave and Current Exposure and Seagrass Conditions on Badi Island, Pangkajene Regency. Undergraduate Thesis. Universitas Hasanuddin, Makassar. [Indonesian]

Duarte CM, Dennison WC, Orth RJW, Carruthers TJB. 2008. The charisma of coastal ecosystems: Addressing the imbalance. Estuar Coast J CERF 31: 233-238. https://doi.org/10.1007/s12237-008-9038-7.

Duarte CM. 1991. Seagrass depth limits. Aquac Bot 40 (4): 363-377. https://doi.org/10.1016/0304-3770(91)90081-F.

Duarte CM. 2000. Seagrass Ecology: An Introduction. Cambridge University Press, Cambridge.

Feng M, Zhang N, Liu Q, Wijffels S. 2018. The Indonesian throughflow, its variability and centennial change. Geosci Lett 5: 3. https://doi.org/10.1186/s40562-018-0102-2.

Hernawan UE, Nurul DMS, Indarto HS, Suyarso, Marindah YI, Kasih A, Rahmat. 2017. Status of Seagrass Beds in Indonesia 2017. Oceanography Research Center - LIPI, Jakarta. [Indonesian]

Hu W, Zhang D, Chen B, Liu X, Ye X, Jiang Q, Zheng X, Du J, Chen S. 2021. Mapping seagrass conservation and restoration priorities. Ecol Indic 129: 107960. https://doi.org/10.1016/j.ecolind.2021.107960.

Janßen A, Wizemann A, Klicpera A, Satari DY, Westphal H, Mann T. 2017. Sediment composition and facies of Coral Reef Islands in the Spermonde Archipelago, Indonesia. Front Mar Sci 4: 144. https://doi.org/10.3389/fmars.2017.00144.

Jompa J, Moka W, Yanuarita D. 2005. Kondisi Ekosistem Perairan Kepulauan Spermonde: Keterkaitannya dengan Pemanfaatan Sumberdaya Laut di Kepulauan Spermonde. Divisi Kelautan Pusat Kegiatan Penelitian, Universitas Hasanuddin. [Indonesian]

Kartika I. 2019. Characterization of Reflection Values using Sentinel-2A Imagery: Barrang Caddi Island. [Undergraduate Thesis]. Universitas Hasanuddin, Makassar. [Indonesian]

Kilminster K, McMahon K, Waycott M, Kendrick GA, Scanes P, McKenzie L, O'Brien KR, Lyons M, Ferguson A, Maxwell P, Glasby T. 2015. Unravelling complexity in seagrass systems. Sci Total Environ 534: 97-109. https://doi.org/10.1016/j.scitotenv.2015.04.061.

Kurniawan F, Arkham MN, Rustam A, Rahayu YP, Adi NS, Adrianto L, Damar A. 2020. The economic value of seafood production is supported by seagrass. IOP Conf Ser Earth Environ Sci 414: 012008. https://doi.org/10.1088/1755-1315/414/1/012008.

Kurniawan F, Digdo AA, Darus RF, Anggraini NP, Ismet MS, Wicaksono P, Kiswara W. 2024. First record of *Ruppia brevipedunculata* in Indonesia. Aquat Bot 195: 103806. https://doi.org/10.1016/j.aquabot.2024.103806.

La Nafie YA. 2016. Seagrass Responses to Interacting Abiotic Stresses. Dissertation. Radboud University, Nijmegen.

Mashoreng S, Isyrini R, Inaku DF. 2020. Decline in seagrass carbon uptake on Bonebatang Island, Spermonde Archipelago, Indonesia, during the Period of 2001-2017. IOP Conf Ser Earth Environ Sci 564: 012028. https://doi.org/10.1088/1755-1315/564/1/012028.

Mashoreng S, La Nafie YA, Selamat B, Isyrini R, Amri K. 2021. Changes in seagrass carbon stock: implications of decreasing area and percentage cover of seagrass beds in Barranglompo Island, Spermonde Archipelago, South Sulawesi, Indonesia. IOP Conf Ser Earth Environ Sci 763: 012014. https://doi.org/10.1088/1755-1315/763/1/012014.

Mashoreng S, Selamat MB, Amri K, La Nafie YA. 2018. Hubungan antara persen penutupan dan simpanan karbon lamun. Jurnal Akuatika Indonesia 3 (1): 74-83. https://doi.org/10.24198/jaki.v3i1.23437. [Indonesian]

McKenzie LJ, Nordlund LM, Jones BL Cullen-Unsworth LC, Roelfsema C, Unsworth KF. 2020. The global distribution of seagrass meadows. Environ Res Lett 15: 074041. https://doi.org/10.1088/1748-9326/ab7d06.

Ministry of Environment. 2004. Decree of the Minister of Environment Number 51 of 2004 Concerning Seawater Quality Standards. Ministry of Environment, Jakarta. [Indonesian]

Ministry of Marine Affairs and Fisheries of the Republic of Indonesia. 2025. Map of Coral Reefs and Seagrass Meadows of Indonesia. Ministry of Marine Affairs and Fisheries, Jakarta. [Indonesian]

Muqorrabin MA, Nurdin N, Mashoreng S, Bahar A, Selamat MB. 2024. Seagrass Mapping Using Unmanned Aerial Vehicle (UAV) Using OBIA (Object Based Image Analysis) Method at Pulau Barrang Lompo. The 7th Nat Geomat Sem 2024, 2 December 2024, Cibinong.

Murphy EP, Dunic JC, Adamczyk EM, Bittick SJ, Côté IM, Cristiani J, Geissinger EA, Gregory RS, Lotze HK, O'Connor MI, Araújo CAS, Rubidge EM, Templeman ND, Wong MC. 2021. From Coast to Coast to Coast: Ecology and Management of Seagrass Ecosystems Across Canada. FACETS. https://doi.org/10.1139/facets-2020-0020.

Nur S, Nurdjaman S. 2025. Temporal assessment of seagrass degradation in Singkep and Lingga Islands. Coast Ocean J 9 (1): 20-33. https://doi.org/10.29244/coj.v9i1.61813.

Ondiviela B, Losada IJ, Lara JL, Maza M, Galván C, Bouma TJ, van Belzen J. 2014. The role of seagrasses in coastal protection in a changing climate. Coast Eng 87: 158-168. https://doi.org/10.1016/j.coastaleng.2013.11.005.

Rahayu YP, Solihuddin T, Kusumaningtyas MA, Ati RNA, Salim HL, Rixen T, Hutahaean AA. 2019. The sources of organic matter in seagrass sediments and their contribution to carbon stocks in the Spermonde Islands, Indonesia. Aqua Geochem 25 (2019): 161-178. https://doi.org/10.1007/s10498-019-09358-7.

Rais M. 2021. Estimation of Seagrass Bed Carbon Stock using SPOT-7 Imagery. [Undergraduate Thesis]. Universitas Hasanuddin, Makassar. [Indonesian]

Randayani PM, Jailani, Sari LI. 2019. Relationship between substrate type and the number of seagrass stands in Karang Kiampau, Bontang City, East Kalimantan. Jurnal Aquarine 6 (2): 65-72.

Risandi J, Rifai H, Lukman KM, Sondak CFA, Hernawan UE, Quevedo JMD, Hidayat R, Ambo-Rappe R, Lanuru M, McKenzie L, Kohsaka R, Nadaoka K. 2023. Hydrodynamics across seagrass meadows. Front Earth Sci 11: 1034827. https://doi.org/10.3389/feart.2023.1034827.

Salim D, Ambo-Rappe R, Mashoreng S, Kadir NN, Zakaria MH, Kiswara W. 2024. Potential threats to seagrass in Tanah Bumbu District. Biodiversitas 25 (5): 1882-1889. https://doi.org/10.13057/biodiv/d260507.

Selamat MB, Ambo-Rappe R, Amri K, Mashoreng S, Nafie YAL, Lanuru M. 2025. Seasonal change detection of seagrass extent using Google Earth Engine. BIO Web Conf 185: 05002. https://doi.org/10.1051/bioconf/202518505002.

Shen J, Wu Z, Yin L, Chen S, Cai Z, Geng X, Wang D. 2022. Salt tolerance mechanism of *Thalassia hemprichii*. Front Plant Sci 13: 975251. https://doi.org/10.3389/fpls.2022.975251.

Short FT, Polidoro B, Livingstone SR, Carpenter KE, Bandeira S, Bujang JS, Calumpong HP, Carruthers TJ, Coles RG, Dennison WC, Erftemeijer PL. 2011. Extinction risk assessment of the world's seagrass species. Biol Conserv 144 (7): 1961-1971. https://doi.org/10.1016/j.biocon.2011.04.010.

Supriadi, Kaswadji RF, Bengen DG, Hutomo M. 2012. Komunitas lamun di Pulau Barranglompo Makassar: Kondisi dan karakteristik habitat. Maspari J 4 (2): 148-158. [Indonesian]

Thalib MS. 2017. Classification of Seagrass Cover using Sentinel-2A Data in Bontosua Island. [Undergraduate Thesis]. Universitas Hasanuddin, Makassar. [Indonesian]

Unsworth RKF, Ambo-Rappe R, Jones BL, La Nafie YA, Irawan A, Hernawan UE, Moore AM, Cullen-Unsworth LC. 2018. Indonesia's globally significant seagrass meadows are under threat. Sci Total Environ 634: 279-286. https://doi.org/10.1016/j.scitotenv.2018.03.315.

Veettil BK, Ward RD, Lima MDAC, Stankovic M, Hoai PN, Quang NX. 2020. Opportunities for seagrass research derived from remote sensing. Ecol Indic 117: 106560. https://doi.org/10.1016/j.ecolind.2020.106560.

Waycott M, Duarte CM, Carruthers TJ, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck KL Jr, Hughes AR, Kendrick GA, Kenworthy WJ, Short FT, Williams SL. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proc Natl Acad Sci USA 106 (30): 12377-12381. https://doi.org/10.1073/pnas.0905620106.

Widhah SF, Ambo-Rappe R, Adrianto L. 2025. Bibliometric Study on Seagrass Research in the Spermonde Archipelago. BIO Web Conf 185 (14): 01004. https://doi.org/10.1051/bioconf/202518501004.

Yushra, Adiguna GS, Sasongko LW, Widyastuti RP. 2020. Estimation of sediment carbon stock in seagrass meadow areas. Manafish J 1 (1): 43-57. https://doi.org/10.31573/manfish.v1i01.41.

Zhang Q. 2016. Iron and Copper Absorption Patterns in *Zostera marina*. [Master's Thesis]. Ocean University of China, Qingdao. [Chinese]