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Research Article

Seagrass Ecosystem Assesment for Dugong Conservation: Integrating Anthropogenic Activites and Oceanographic Parameters in East Java's Coastal Waters

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Abstract

This study aims to assess the ecological status of seagrass meadows and their relationship with dugong (*Dugong dugon*) habitats across four distinct ecological regions in East Java, Indonesia. Field assessments were conducted to evaluate seagrass community structure, oceanographic parameters, and the intensity of human activities. Seagrass distribution was mapped using Sentinel-2A satellite imagery, while seagrass health was evaluated through the Seagrass Ecological Quality Index (SEQI) and Importance Value Index (IVI). Statistical analyses, including Analysis of Variance (ANOVA) and Principal Component Analysis (PCA), were employed to identify significant differences and key environmental drivers. The results revealed marked spatial variation in oceanographic characteristics and seagrass coverage ($p < 0.05$). PCA showed that anthropogenic factors particularly marine space utilization such as aquaculture and coastal development were major contributors to seagrass degradation. Elevated nutrient concentrations were also associated with declining seagrass health, indicating land-based pollution as a dominant stressor. These findings underline the urgent need for integrated coastal zone management. Strengthening conservation policies, reducing terrestrial runoff, and implementing sustainable marine spatial planning are critical to safeguard seagrass ecosystems and ensure the long-term survival of dugong populations in Indonesian waters.

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1. Introduction

The dugong (*Dugong dugon* Müller, 1776) is a marine mammal species classified as vulnerable according to the International Union for Conservation of Nature (IUCN) Red List, with populations showing a declining trend primarily due to by-catch, hunting, and habitat degradation. In 2023, a stranded dugong was reported in the coastal waters of East Java, highlighting the ongoing threats to this species in Indonesian waters (Dewi *et al.,* 2024b). As herbivorous marine mammals, dugongs rely heavily on seagrass beds for both habitat and primary food sources (McGowan *et al.,* 2023; Thibault *et al.,* 2024) a large marine mammal herbivore of the Indo-Pacific, is vulnerable to extinction at a global scale due to a combination of human-related threats including habitat degradation. The species forages on seagrass habitats (marine phanerogams. The degradation or loss of these seagrass ecosystems can lead to severe consequences, including malnutrition, reduced reproductive success, and increased mortality rates, further exacerbating its population decline (Cleguer *et al.,* 2020; Cleguer and Marsh, 2023).

Seagrass beds provide essential ecological services not only for dugongs but also as habitats for fish, crustaceans, and mollusks (Irawan *et al.,* 2018; Peters *et al.,* 2015; Scott *et al.,* 2018) there exists limited evidence in the United Kingdom (UK. Seagrass beds also play a significant role in mitigating coastal erosion by stabilizing sediments and reducing wave energy (Aulia *et al.*, 2021; Dewi *et al.*, 2024; do Amaral Camara Lima *et al.*, 2023) namely: Kondang Merak Beach (St 1. Furthermore, they contribute to global climate regulation through their ability to store blue carbon in underwater sediments, making them critical for long-term carbon sequestration (Dewi *et al.,* 2024; Hernawan *et al.,* 2021; Wahyudi *et al.,* 2022) multiple threats are putting pressure on this valuable habitat. Seagrass conservation and restoration is essential to maintain the carbon sequestration service, along with the other ecosystem services (e.g., fisheries production. The ecological importance of seagrass meadows extends to maintaining marine biodiversity and supporting fisheries, which are vital for coastal communities.

Human activities related to coastal and marine spatial utilization further intensify pressure and threaten the health of seagrass ecosystems. The expansion of seaweed aquaculture in the Indo-Pacific has been linked to seagrass decline due to increased nutrient loads and habitat alterations (Unsworth *et al.*, 2018). Similarly, physical disturbances from activities such as clam digging and fishing have contributed to habitat fragmentation and structural degradation of seagrass ecosystems. Additionally, oceanographic factors such as changes in water temperature, salinity, and light availability play a critical role in the health of seagrass meadows (Liu *et al.,* 2023). Climate change is expected to amplify these stressors, with elevated temperatures affecting seagrass physiological processes and shifts in freshwater inflows altering salinity conditions, leading to further ecosystem instability (Shen *et al.,* 2022; Tang and Hadibarata, 2022).

Despite their ecological significance, seagrass ecosystems are facing rapid degradation worldwide due to increasing anthropogenic pressures and environmental changes. Coastal modifications, wave action, and sedimentation have been identified as key drivers of seagrass decline in various regions (Losciale *et al.,* 2022a; Losciale *et al.,* 2022b; Ramírez-Zúñiga *et al.,* 2024) one of the world's greatest natural assets, are globally declining due to direct-anthropogenic (e.g., pollution, coastal development, run-off. Similar trends are unfolding in Indonesia through significant reductions in both the extent and health of its seagrass beds (Hernawan *et al.,* 2021; Rahmawati *et al.,* 2017, 2022) multiple threats are putting pressure on this valuable habitat. Seagrass conservation and restoration is essential to maintain the carbon sequestration service, along with the other ecosystem services (e.g., fisheries production. In East Java, seagrass cover has been classified as moderate, yet detailed information regarding its vegetation structure remains lacking (Dewi *et al.,* 2024a). The dominant seagrass species include *Thalassia hemprichii* Ascherson, 1871; *Cymodocea rotundata* Ehrenberg & Hemprich ex Ascherson, 1871; *Cymodocea serrulata* (R. Brown) Ascherson & Magnus, 1870; *Halodule uninervis* (Forsskål) Ascherson, 1882; *Halodule pinifolia* (Miki) Hartog, 1970; *Halophila ovalis* (R. Brown) Hooker f., 1858; *Enhalus acoroides* (Linnaeus f.) Royle, 1839; and *Syringodium isoetifolium* (Ascherson) Dandy, 1939 (Dewi *et al.,* 2024a; Hernawan *et al.,* 2021). The spatial extent varies by site, with patchy to continuous meadows found in locations such as Bawean Island, Madura Strait, and south coast of Banyuwangi, although most areas remain under-reported due to limited monitoring. Understanding the ecological complexity and human-mediated impacts to seagrass and local dugong population is crucial for provincial government in developing effective conservation strategies (Sunuddin *et al.,* 2016), previously enacted under Indonesian Law No. 23/2014, particularly managing the sustainability of ecosystem services provided to coastal and fisher communities.

Given these challenges, a comprehensive analysis of seagrass bed vegetation structure, water quality parameters, and substrate conditions is essential for effective conservation and management. Investigating patterns of marine and coastal space utilization, alongside assessing oceanographic conditions, will provide insights into the factors influencing seagrass health and distribution. Understanding the interactions between spatial utilization and oceanographic components across seagrass habitats is necessary for evaluating the extent of anthropogenic and environmental impacts on these ecosystems.

Recent studies provide valuable evidence of the occurrence and ecological context of dugongs (*Dugong dugon*) in East Java waters (Dewi *et al.,* 2024; 2025). The 2025 study reported the first genetically confirmed presence of a dugong in the Java Sea region through DNA barcoding of a stranded specimen found near the northern coast of East Java. This finding not only confirmed the species' existence in the region but also highlighted the lack of prior molecular data for Indonesia's main islands. These include coastal development, sedimentation, pollution, and reduced water quality. Combined, the findings emphasize the urgent need for integrated conservation strategies, including habitat protection, ecological monitoring, and marine spatial planning, to safeguard dugongs and the seagrass ecosystems they depend on in East Java.

Previous research indicates that the presence of dugongs (*Dugong dugon*) is strongly correlated with the availability of seagrass meadows, particularly pioneer species such as *Halodule uninervis (Forsskål) Ascherson, 1882* and *Halophila ovalis (R. Brown) Hooker f., 1858* is influenced by oceanographic factors such as tides and winds, as well as anthropogenic pressures including fishing activities and vessel traffic (De Iongh *et al.,* 2007; Budiarsa *et al.,* 2021; Sheppard *et al.,* 2010; Al-Asif *et al.,* 2022). A study at Liki Island, Papua, also confirms the spatial relationship between dugong sightings and the distribution of seagrass species, reinforcing the ecological dependence of dugongs on specific vegetation zones (Nugraha *et al*., 2019). However, previous studies were conducted outside East Java (in Sulawesi and Kalimantan) and were more partial in nature, not yet integrating oceanographic aspects and human activities quantitatively within a single spatiotemporal ecological framework. This study aims to (1) observe patterns of marine and coastal space utilization within the designated study areas, (2) examine the general oceanographic conditions affecting seagrass habitats, (3) assess the community structure and health status of seagrass meadows, and (4) analyze the interactions between spatial utilization and oceanographic components in seagrass environments. By elucidating the relationship between seagrass vegetation structure and environmental parameters, the findings will contribute valuable knowledge for dugong conservation efforts and the sustainable management of marine ecosystems in East Java.

2. Materials and Methods

This study was carried out from August to October 2024 through several stages, including data collection, sample processing, analysis, and interpretation. Fieldwork was conducted at four stations (Figure 1), selected based on a combination of ecological representativeness and historical or recent indications of dugong presence. These stations included: Bawean Island (Station 1), Sapulu Beach – Northwest Madura Island (Station 2), Tabuhan Island – Banyuwangi (Station 3), and Plengkung Beach – Alas Purwo National Park (Station 4). Each site represents a distinct ecological zone, ranging from small island ecosystems in the Java Sea (Station 1), northern coastal zones with high anthropogenic activity (Station 2), transitional Bali Strait waters (Station 3), to relatively undisturbed southern coastal waters exposed to the Indian Ocean (Station 4). Previous dugong sightings and stranding reports have been recorded in areas near Stations 1, 2, and 4, supporting their selection as potentially suitable or critical habitats for *Dugong dugon*. Therefore, site selection was intended to assess seagrass habitat conditions in both historically occupied areas and ecologically diverse regions of East Java's coastline.

2.1 Materials

2.1.1 The equipment

This study utilized a range of instruments to support data collection and analysis. The field equipment included a Global Positioning System (GPS) for recording geographic coordinates, measuring tapes for distance measurement, and quadrat transects for vegetation sampling. Underwater surveys were conducted using basic diving equipment, underwater cameras for visual documentation, and underwater whiteboards with pencils for in situ data recording. Data analysis was conducted using a laptop equipped with Microsoft Word and Microsoft Excel for basic data management, as well as R Studio and QGIS for statistical and spatial analysis. R Studio was specifically employed to perform Analysis of Variance (ANOVA), boxplot visualization, and Principal Component Analysis (PCA), supported by the ggplot2 package, which was installed using the command *install.packages* (*ggplot2*).

2.1.2 The materials

The materials used in this study included plastic samples collected from the field for further analysis and silica gel as a preservative to maintain sample in

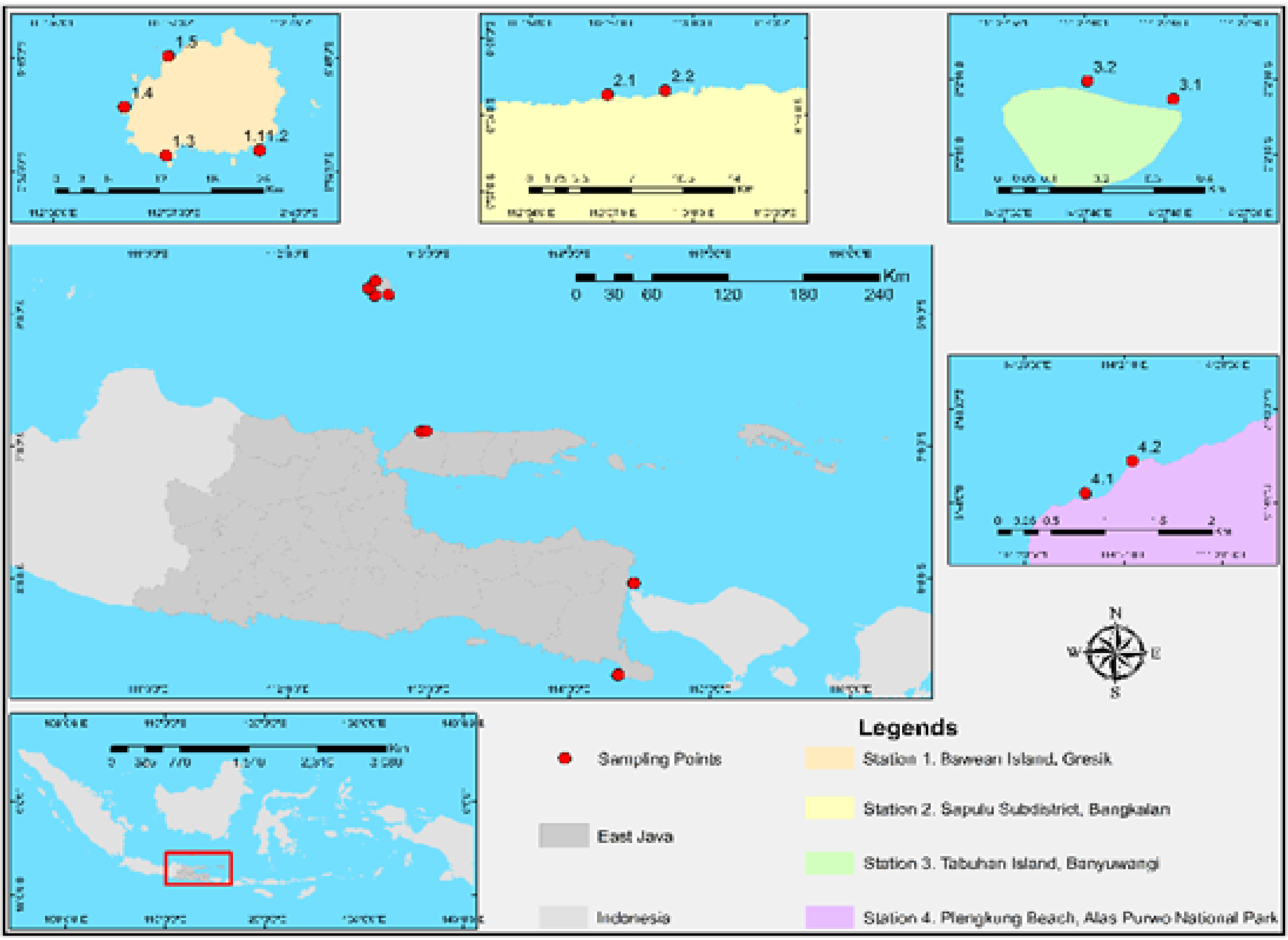

Figure 1. Study locations at four stations: Bawean Island - Gresik (Station 1), Sapulu Sub-district - Bangkalan (Station 2), Tabuhan Island - Banyuwangi (Station 3), and Plengkung Beach - Alas Purwo National Park (Station 4). The study area comprised four stations, each representing distinctive aquatic environments in East Java: the northern Java Sea waters (Station 1), Madura Island waters (Station 2), Bali Strait waters (Station 3), and the southern waters (Station 4).

tegrity during storage. In addition, Sentinel-2 satellite imagery obtained from the Copernicus Open Access Hub was utilized to support spatial analysis and mapping of the study area.

2.1.3 Ethical approval

This study proposal was reviewed and obtained two official permits. The first permit was an Ethics Eligibility Certificate issued by the Bioscience Laboratory of Universitas Brawijaya, with the certificate number 166–Kep-UB–2023. According to institutional policy, this ethical clearance remains valid for a period of two years from the date of issuance and is currently still in effect. The second document is a Recommendation Letter for the SDG Access Permit, Collection, and Delivery of SATS-DN *Dugong* and seagrass plant samples, issued by the Secretariat of the Biodiversity Science Authority, National Research and Innovation Agency (SKIKH–BRIN) under letter number B-4860/IV/KS.00/6/2024. This letter also remains valid and applicable as of the time of this study.

2.2 Methods

Marine and coastal space utilization data were collected through secondary sources, including structured questionnaires, interviews, and official documents from East Java Regional Regulation No. 1 of 2014. Interviews employed systematically structured questionnaires to ensure statistical validity and facilitate geographic data tracking. Oceanographic data collection involved direct field measurements using a water quality checker for parameters such as transparency, depth, substrate type, temperature, salinity, dissolved oxygen (DO), and pH, complemented by secondary data analysis. Additional parameters, including current velocity, wave height, tidal patterns, and nutrient concentrations (nitrate and phosphate), were sourced from the *Global Ocean Physics Analysis and Forecast* and *Global Wave Analysis and Forecast* datasets, ensuring high-resolution temporal and spatial data accuracy (Emeka *et al*., 2023).

Seagrass bed mapping was conducted through site selection, image analysis, and accuracy validation. Sentinel-2A satellite imagery was utilized due to its superior geometric and radiometric correction capabilities, suitable for monitoring seagrass ecosystem dynamics. Depth correction was applied using the Lyzenga Equation (Depth Invariant Index) to enhance benthic data accuracy (Rosalina *et al*., 2023). Image classification followed a supervised approach using the *Maximum Probability* algorithm, validated through confusion matrix analysis.

Field sampling was performed using three 100-meter line transects perpendicular to the shoreline, with quadrat sampling (50 cm × 50 cm) at 10-meter intervals (McKenzie and Yoshida, 2013; Rahmawati *et al*., 2022). Data collection included seagrass species distribution, density, coverage, and frequency, recorded following a modified *Seagrass Watch* protocol. Species identification was conducted macroscopically at the Fisheries and Marine Resources Exploration Laboratory, Universitas Brawijaya, using morphological characteristics and identification guides (Rahmawati *et al*., 2017). The seagrass community structure was analyzed using the Importance Value Index (IVI), while seagrass ecosystem health was evaluated using the Seagrass Ecological Quality Index (SEQI), incorporating four core parameters: seagrass type and coverage, macroalgae and epiphyte presence, and water clarity (Hernawan *et al*., 2021; Shrestha *et al*., 2000; Sukandar and Dewi, 2017).

2.3 Analysis Data

Coastal and marine space utilization data were analyzed descriptively using bar charts and heatmaps, while oceanographic and seagrass ecosystem variables were compared across stations using ANOVA and visualized with box plots. The relationships among space utilization, oceanographic parameters, and seagrass ecosystem characteristics were examined through Principal Component Analysis (PCA). The integration of ANOVA and PCA in ecological research provides powerful tools for analyzing the influences of environmental factors on biological communities (Baur *et al*., 2014; Metsalu and Vilo, 2015).

3. Results and Discussion

3.1 Results

3.1.1 Utilization of coastal and marine space

Heatmap analysis revealed a diverse distribution of anthropogenic activities across the four monitored stations, indicating spatial variability in coastal and marine resource utilization (Figure 2). Stations 1 and 2 exhibit high activity intensity (indicated by dark blue) in almost all types of activities, with a slight decrease in intensity for Mining and Tourism/Cultural Heritage activities. Meanwhile, Stations 3 and 4 display a different pattern, with generally lower activity intensity (indicated by light blue), except for certain points such as Marine Tourism activities at Station 3 and River-related activities at Station 4, which show high intensity.

3.1.2 Oceanographic parameters

ANOVA analysis indicates that nearly all oceanographic parameters exhibit significant differences among observation stations (p-value < 0.05), including temperature, salinity, and nitrate levels (Figure 3). The box plot visualization presents the distribution of each parameter at each station to visually illustrate these differences.

3.1.3 Seagrass ecosystem

The seagrass species observed in this study include *Halophila ovalis* (R. Brown) Hooker f., 1858; *Thalassia hemprichii* Ascherson, 1871; *Halodule uninervis* (Forsskål) Ascherson, 1882; *Halodule pinifolia* (Miki) Hartog, 1970; *Enhalus acoroides* (Linnaeus f.) Royle, 1839; *Syringodium isoetifolium* (Ascherson) Dandy, 1939; *Cymodocea rotundata* Ehrenberg & Hemprich ex Ascherson, 1871; and *Cymodocea serrulata* (R. Brown) Ascherson & Magnus, 1870. Among these, *H. ovalis*, *H. uninervis*, and *T. hemprichii* were the most dominant, with high coverage and frequency values at multiple sites. Notably, *Halophila ovalis*, known as a preferred forage species for *Dugong dugon* was the most dominant species at Station 1 (Bawean Island), where multiple dugong sightings and strandings were recorded between 2023 and 2024. Additionally, *Thalassia hemprichii* was the dominant species at Station 2 (Bangkalan), where another dugong stranding occurred. These findings suggest that the presence of specific seagrass species, particularly those known to be favored in dugong diets, is closely linked to dugong activity and sightings in East Java waters. Thus, the distribution and abundance of key forage species such as *H. ovalis* and *T. hemprichii* may serve as ecological indicators for potential dugong habitat in the region.

The seagrass meadow area in the study location varies across the observation stations (Figure 4). Station 1 has the largest area, covering 58.48 hectares,

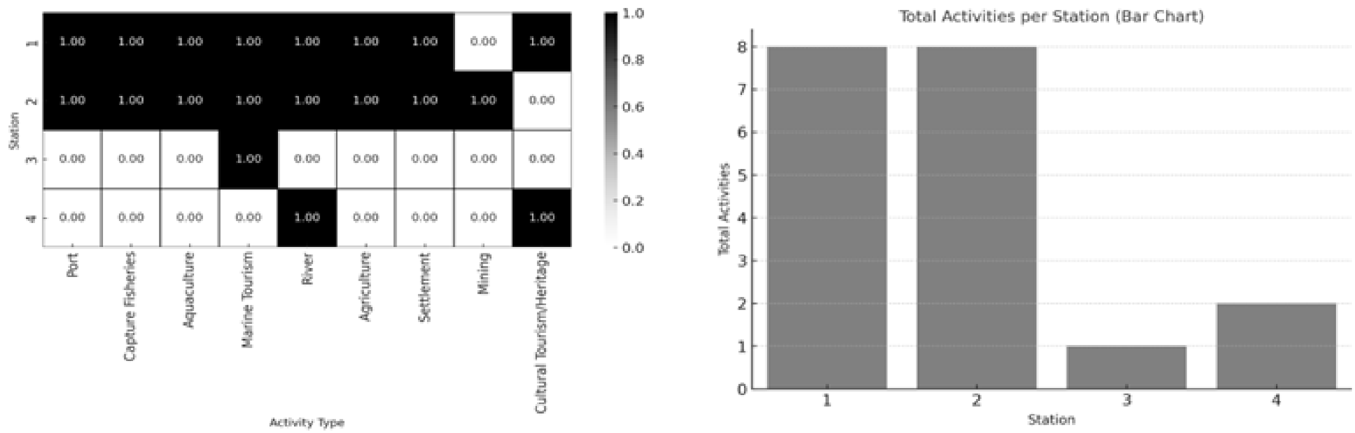

Figure 2. The utilization of coastal and marine space in the study area indicates that resource use activities are more prevalent at Stations 1 and 2 compared to Stations 3 and 4. High activity levels, visualized in black, dominate almost all sectors at Stations 1 and 2, except for Mining and Tourism/Cultural Heritage activities, which exhibit lower intensity. A different pattern is observed at Stations 3 and 4, where activity intensity is generally lower (represented by white), with exceptions for high-intensity Marine Tourism activities at Station 3 and River-related activities at Station 4.

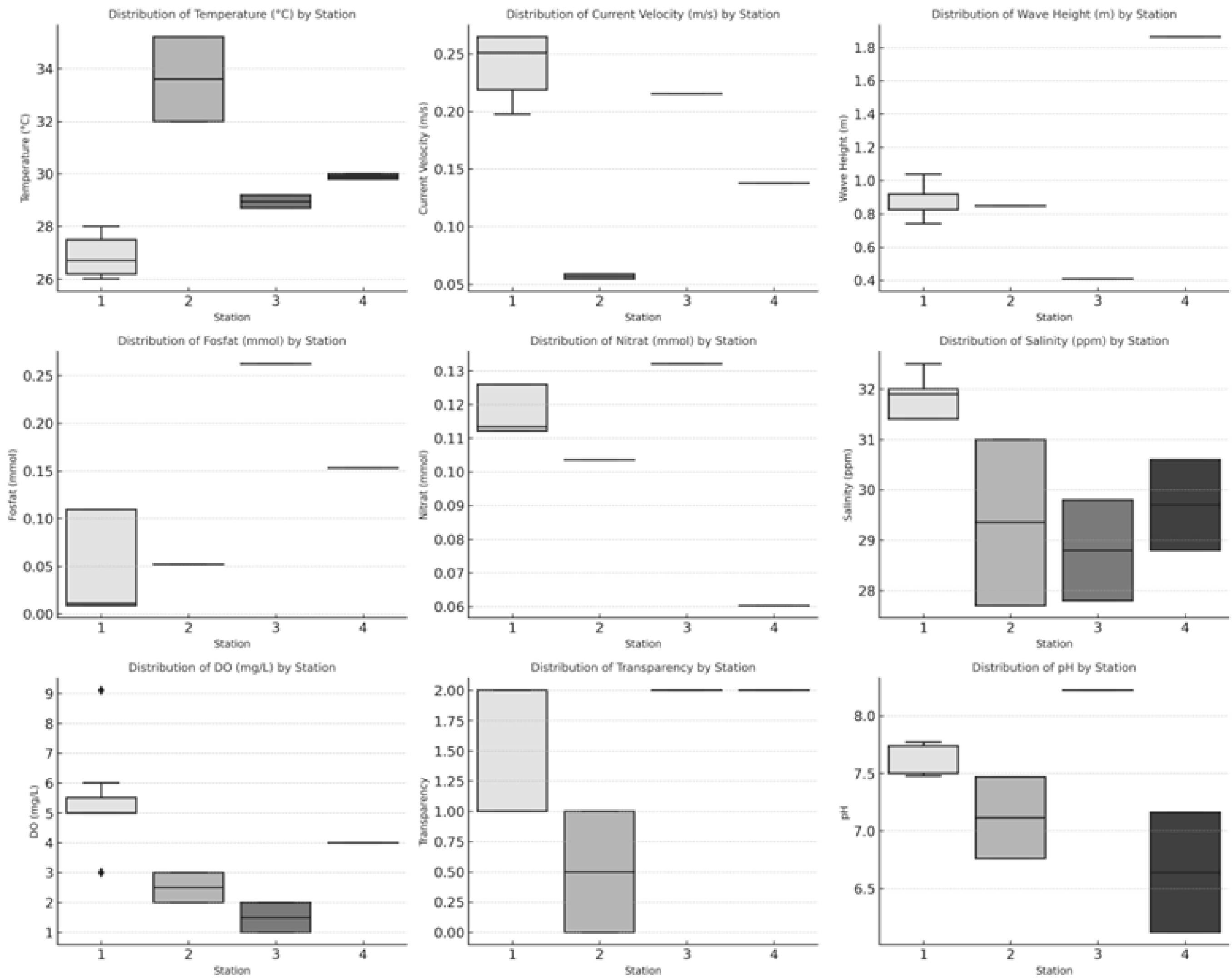

Figure 3. The ANOVA test results indicate significant variation in most oceanographic parameters among the observed stations (p-value < 0.05), including temperature, salinity, and nitrate levels. To facilitate the interpretation of differences between stations, the distribution of each parameter is visualized using a box plot diagram.

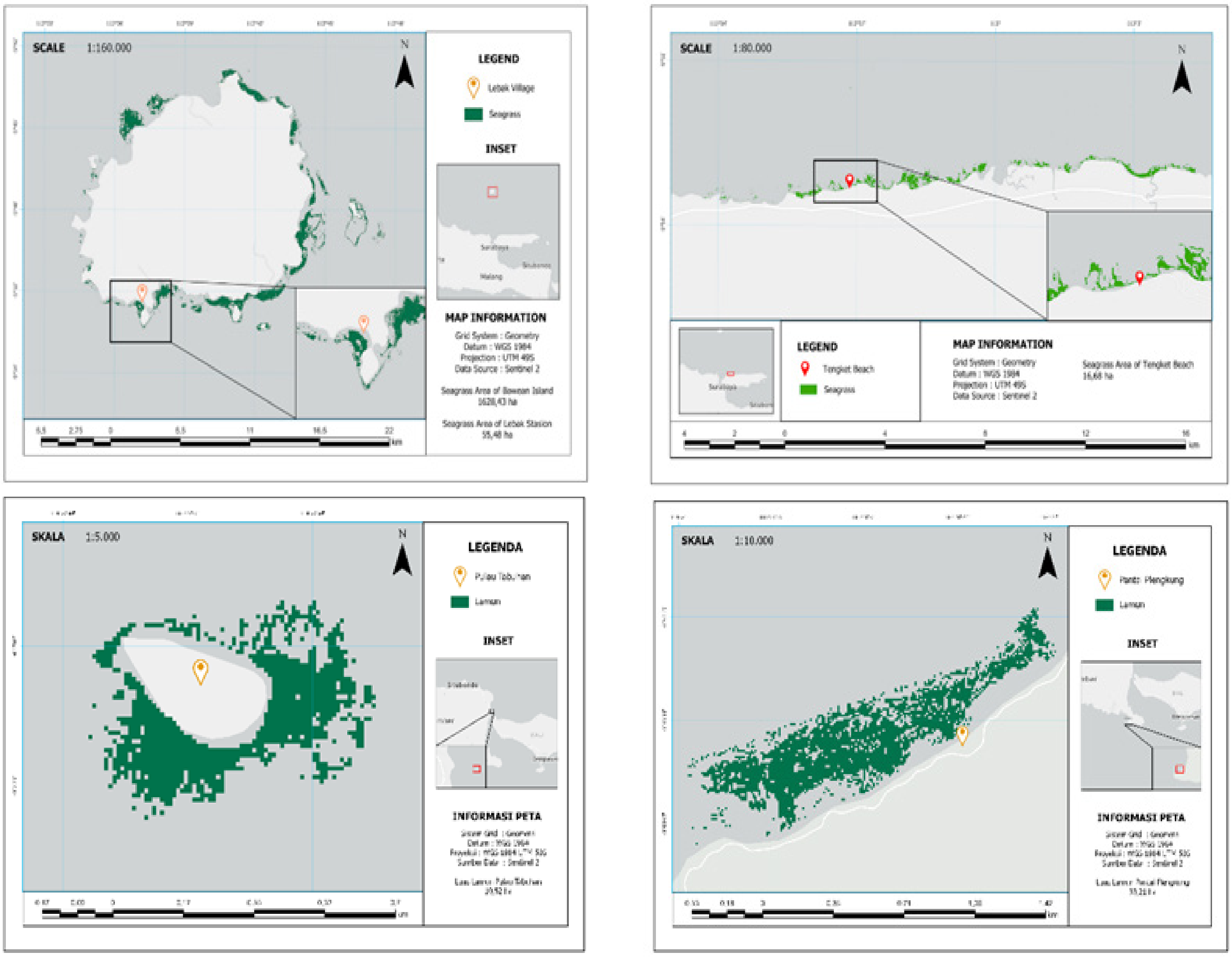

Figure 4. The seagrass meadow area in the study location varies across the observation stations. Station 1 has the largest area, covering 58.48 hectares, indicating a more extensive seagrass ecosystem compared to the other locations.

indicating a more extensive seagrass ecosystem compared to the other locations. Station 2 has an area of 16.68 hectares, while Station 3 has a smaller area of 10.52 hectares. Meanwhile, the seagrass meadow at Station 4 covers 33.21 hectares. Among all stations, Station 1 and Station 4 have significantly larger seagrass areas than Station 2 and Station 3. This variation in area may be influenced by environmental factors such as water conditions, substrate type, and differing anthropogenic pressures at each location. Overall, the distribution of seagrass meadows in the study area suggests that certain stations provide more favorable conditions for seagrass growth and expansion. The ANOVA analysis of the seagrass ecosystem data revealed significant differences among the stations for most seagrass ecosystem traits (p-value < 0.05), including species diversity, shoot density, seagrass cover, and epiphyte coverage (Figure 5).

3.1.4 Connectivity of coastal-marine spatial utilization, oceanography, and seagrass meadows

The Principal Component Analysis (PCA) results show that the first two principal components (PC1 and PC2) are able to explain approximately 68.05% of the total data variability, with PC1 contributing 37.53% and PC2 contributing 30.52% (Figure 6). This indicates that the majority of information in the dataset can be represented in two main dimensions, thus further analysis can focus on the interpretation of PC1 and PC2.

PC1 represents variation primarily influenced by marine space utilization factors, such as the presence of ports, aquaculture, agriculture, and settlements, which have high negative contributions to PC1. Conversely, environmental factors such as phosphate levels in waters, seagrass ecosystem area, and percentage of seagrass cover contribute positively to PC1. This indicates that stations on the negative side of PC1 tend to be more affected by human activities,

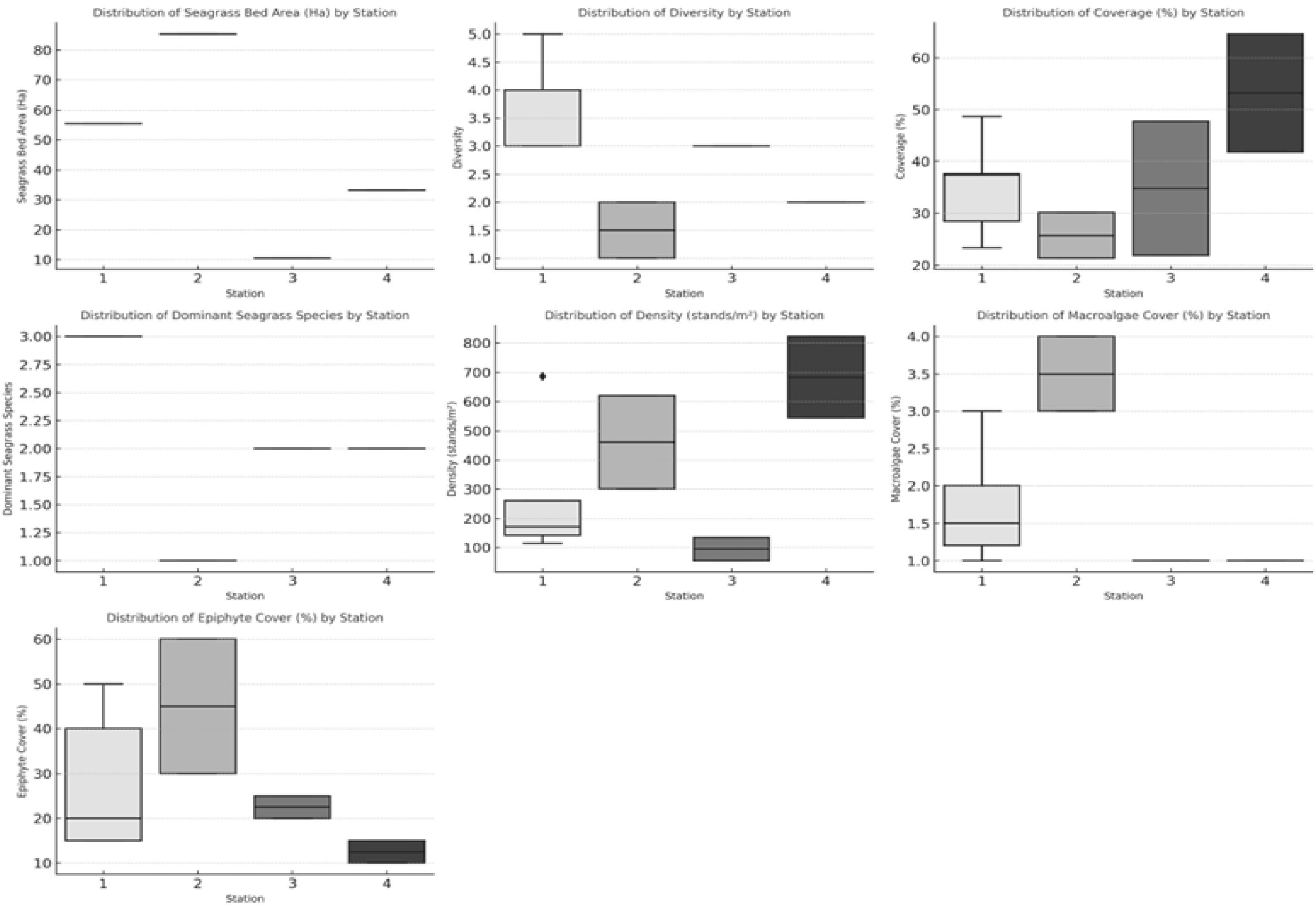

Figure 5. The ANOVA analysis of seagrass ecosystem data demonstrates significant variations among stations in most ecosystem parameters (p-value < 0.05), such as diversity, density, seagrass cover percentage, and epiphyte coverage.

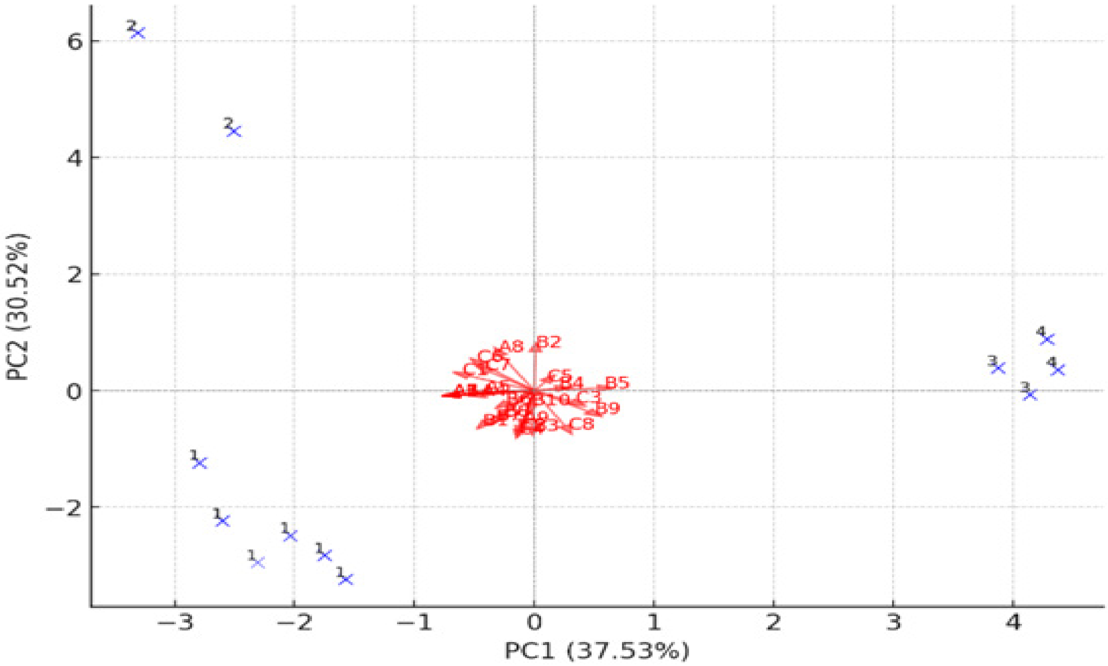

Figure 6. Principal Component Analysis (PCA) explains 68.05% of data variability, with PC1 (37.53%) reflecting human impact versus ecosystem health and PC2 (30.52%) influenced by oceanographic factors. Stations with high anthropogenic pressure (ports, aquaculture, settlements) cluster on the negative PC1 axis, while healthier ecosystems (larger seagrass areas, higher coverage) align positively. Variations along PC2 highlight differences in water temperature, mining activities, and habitat quality, forming distinct ecological groupings across the study area.

while stations on the positive side of PC1 have larger seagrass ecosystems and better environmental conditions.

PC2, on the other hand, is more influenced by oceanographic factors and seagrass habitat quality, such as water temperature, mining activities, and seagrass ecosystem quality index (SEQI), which have positive contributions to PC2. Conversely, seagrass species dominance variables and current velocity show fairly high negative contributions to PC2. This shows that the differences between stations along the PC2 axis are more influenced by physical-chemical factors of the waters, which can determine the presence and dominance of certain seagrass species in a location.

From the distribution of stations in the PCA space, it appears that some stations have similar environmental characteristics as they are close to each other. Conversely, stations that are positioned far apart along PC1 show significant differences in terms of marine space utilization and oceanographic conditions. The dispersion of stations in PC2 indicates that differences in temperature, currents, and seagrass ecosystem quality index also play an important role in forming different ecological groups.

3.2 Discussion

3.2.1 Spatial utilization

The spatial utilization patterns of coastal and marine areas exhibit notable variations across the four seagrass stations, as visualized in the heatmap (Figure 2). Station 1 and 2 demonstrate higher intensity of anthropogenic pressures, particularly from capture fisheries, aquaculture, and maritime transportation. In contrast, Stations 3 and 4 experience relatively lower levels of disturbance, primarily due to limited marine tourism and riverine sedimentation. These human pressures not only affect the health and distribution of seagrass ecosystems (Kusnadi *et al*., 2024; Mascariñas and Otadoy, 2023), but also pose direct threats to dugong survival.

A relevant case study from Bintan Island (Idris *et al.,* 2020) confirmed dugong presence using local ecological knowledge and highlighted that fishing activities including the use of gillnets and fish traps, led to accidental entanglement and mortality. Moreover, boat traffic and coastal disturbances were found to cause dugong avoidance behaviors, even in areas with healthy seagrass cover. This parallels the conditions observed in Station 1 (Bawean) and Station 2 (Sapulu Beach), where intense spatial use for fisheries and marine traffic may directly interfere with dugong movement, increase the risk of physical injury, or even lead to mortality. Such direct interactions are critical when evaluating dugong sustainability, beyond just assessing habitat availability.

3.2.2 Oceanography

The oceanographic conditions among the stations show statistically significant differences ($p < 0.05$) in key parameters, including temperature, salinity, and nitrate concentrations (Figure 3). Variations in temperature, salinity, and nutrient concentrations likely stem from site-specific hydrodynamic processes, including tidal flushing, riverine discharge, and coastal upwelling. Stations experiencing higher temperatures and salinity fluctuations may be more exposed to open-sea influences, whereas stations with higher nitrate concentrations might be receiving nutrient inputs from land-based sources, such as agricultural runoff or urban wastewater (Fraser *et al*., 2012; Grech *et al*., 2012). These findings highlight the role of oceanographic conditions in shaping seagrass ecosystems, as fluctuations in these parameters (temperature, salinity, and nitrate) can influence seagrass productivity, species composition, and overall resilience (Campbell *et al*., 2018; Xu *et al*., 2016).

3.2.3 Seagrass bed

The extent of seagrass meadows across the study sites varies significantly, with Station 1 exhibiting the largest coverage (58.48 ha), followed by Station 4 (33.21 ha), Station 2 (16.68 ha), and Station 3 (10.52 ha) (Figure 4). The observed differences in seagrass coverage may be attributed to variations in environmental conditions, including substrate type, water clarity, and hydrodynamic forces, as well as differing levels of anthropogenic impact (Maxwell *et al*., 2015; Widagti *et al*., 2023). Notably, the larger seagrass meadows at Stations 1 and 4 suggest that these locations may provide more favorable conditions for seagrass establishment as dugong's habitat. The ANOVA results further confirm significant differences ($p < 0.05$) in key seagrass ecosystem parameters, including diversity, density, cover, and epiphyte presence (Figure 5), emphasizing the heterogeneous nature of seagrass distribution in response to environmental and anthropogenic influences (Hernawan *et al*., 2021; Rahmawati *et al*., 2022; Unsworth *et al*., 2018).

3.2.4 Connectivity of coastal-marine spatial utilization, oceanography, and seagrass meadows

In the PCA biplot, Station 1 (S1) is on the negative side of PC1, which indicates higher pressures from human settlement activities and aquaculture. This suggests that the presence of settlements around the Bawean coasts and aquaculture activities can impact water quality and seagrass ecosystem health. Increased nutrient content, such as phosphate and nitrate from fish farming activities and domestic waste, can cause eutrophication, which contributes to decreased water clarity and increased macroalgae growth that can compete with seagrass (Herbert *et al*., 2011) including occurrences of hypersalinity, coupled with a decrease in salinity variability, and (2. Meanwhile, Station 3 (S3) and Station 4 (S4) are on the positive side of PC1, which indicates that both locations have better environmental conditions with relatively larger seagrass beds and lower anthropogenic pressure. These conditions can support higher seagrass diversity and density, which contributes to the high SEQI (Seagrass Ecosystem Quality Index) values at both stations (Losciale *et al*., 2022b).

Meanwhile, Station 2 (S2) is closer to the center of the PCA coordinates, indicating that this location has more balanced environmental characteristics compared to other stations. Oceanographic factors, such as currents, temperature, and water clarity, are likely the main determinants affecting the seagrass ecosystem at S2. This condition may indicate that although S2 does not experience as much anthropogenic pressure as S1, fluctuations in oceanographic factors still play a role in determining the dynamics of the seagrass ecosystem at this location (Al-Asif *et al*., 2022).

Furthermore, clustering results using the K-Means method show that Station 1 forms its own cluster, indicating very different environmental characteristics compared to other stations. This confirms that high anthropogenic pressure at S1 can cause degradation of seagrass ecosystems, possibly marked by decreased seagrass coverage, increased epiphyte growth, and decreased water clarity (Budiarsa *et al*., 2021; Tis'In *et al*., 2023). Station 2 also forms its own cluster, showing that oceanographic conditions are more dominant in influencing seagrass characteristics at this location. Station 3 and Station 4 are in one cluster, showing that both locations have similar environmental conditions, with less anthropogenic influence and more stable seagrass conditions (Giakoumi *et al*., 2015).

The PCA biplot results show clear environmental gradients across the stations, with Station 1 (Bawean Island) and Station 2 (Sepulu, Bangkalan) influenced by high anthropogenic activities such as aquaculture, fisheries, and coastal settlements. These pressures are known to degrade seagrass health, impacting dugong habitat quality and potentially leading to behavioral displacement. On the other hand, Station 3 (Tabuhan Island) and Station 4 (Plengkung, TN Alas Purwo) exhibit better ecological conditions, with higher SEQI values and lower anthropogenic disturbance. These findings can directly inform the refinement of East Java's RZWP3K by identifying key ecological zones that merit higher protection status or restricted-use zones, particularly in areas with confirmed dugong presence and high seagrass health.

In Bawean Island and Sepulu, where dugong presence was genetically confirmed through DNA barcoding and seagrass beds were extensive but under pressure, community-based conservation areas or no-take zones can be proposed under RZWP3K revision, or as extensions to national MPA networks. Meanwhile, Tabuhan and Plengkung could be developed as seagrass monitoring sites or rehabilitation zones, supporting broader ecosystem services and dugong habitat connectivity. This aligns with the findings in Bintan (Idris *et al*., 2020), where dugong survival was tightly linked to spatial planning, and failure to manage fishing gear and tourism development led to frequent entanglements and hunting.

4. Conclusion

This study examined the relationships between coastal-marine spatial utilization, oceanographic parameters, and seagrass ecosystem conditions across four stations in East Java, further providing insights for dugong habitat conservation. Distinct environmental gradients affect seagrass bed distribution in contrast to anthropogenic pressures, thus site-specific management approach is required. Recommendations for provincial government to support seagrass and dugong conservation in East Java are to implement These patterns highlight the necessity for site-specific management approaches: implementing stricter mitigation measures at Station 1, establishing monitoring programs for oceanographic fluctuations at Station 2, and prioritizing conservation efforts at Stations 3 and 4. These specific measures reflects the complexity nature of seagrass socio-ecological system, which eventually support dugong and other vulnerable species associated to seagrass habitats.

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Authors' Contributions

All authors actively participated in the development of this manuscript. Citra carefully collected data, skillfully drafted the manuscript, and creatively designed the figures. Gatot, Slamet, and Hagus played an important role in conceptualizing the research. Sekar, Bambang, Adriani, and Andik provided critical revisions that improved the quality of the article. Sukandar and Dewa adjusted the research concept and scientific article to the research funding. Through open discussions, all authors contributed expertise to refine the results and complete the manuscript.

Conflict of Interest

The authors declare that the study was conducted in the absence of any commercial or financial relationships with potential conflicts of interest.

Declaration of Artificial Intelligence (AI)

The authors acknowledge the use of ChatGPT and Claude for language refinement, summarization, and visualization of data analysis results; as well as Consensus and Scite for accessing recent literature during the preparation of this manuscript. All AI-generated content was thoroughly reviewed, edited, and validated to ensure accuracy and originality. Full responsibility for the final content of the manuscript rests with the authors. To ensure transparency and support the review process, a detailed explanation of the use of these tools is provided in the "Introduction" or "Materials and Methods" section of the manuscript, in accordance with the publisher's ethical guidelines.

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