SEDIMENT COMPOSITION AND ITS ROLE IN SHAPING SEAGRASS BIODIVERSITY IN VOLCANIC ISLAND ENVIRONMENTS: A CASE STUDY FROM TERNATE ISLAND, INDONESIA

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Abstract

Seagrass ecosystems are crucial in coastal marine environments, particularly small volcanic islands with highly dynamic sediment composition. This study examines the influence of sediment fraction characteristics on seagrass biodiversity distribution around Ternate Island, Indonesia, a geologically active volcanic island. Seagrass community structure and sediment properties were assessed across three vertical zones at four sampling stations. The study identified seven seagrass species: Enhalus acoroides, Thalassia hemprichii, Cymodocea rotundata, Cymodocea serrulata, Syringodium isoetifolium, Halophila ovalis, and Halodule pinifolia. Zone 1 exhibited the highest seagrass coverage, while Zone 3 had the lowest coverage, influenced by sediment composition and hydrodynamic exposure. Sediment analysis revealed that medium sand was the predominant fraction across all zones, with fine sand and mud playing a key role in enhancing seagrass biodiversity. Multivariate statistical analysis using Principal Component Analysis (PCA) and Pearson correlation identified significant relationships between sediment composition and seagrass ecological parameters. These findings provide critical insights into the interactions between sediment properties and seagrass distribution, informing conservation strategies for seagrass ecosystems in volcanic island environments.

Keywords: Seagrass distribution; Sediment fraction; Conservation; Volcanic islands; Ternate Island

Introduction

Seagrass ecosystems serve as vital marine habitats, contributing to biodiversity, carbon sequestration, sediment stabilization, and coastal protection [1], [2], [3]. Their presence is especially significant on small volcanic islands, where sediment dynamics are influenced by geological activity, hydrodynamic processes, and anthropogenic disturbances [4], [5], [6]. Despite their ecological importance, seagrass ecosystems in volcanic island morphotypes remain understudied, particularly in the context of sediment fraction characteristics and their influence on species distribution.

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Ternate Island, part of the North Maluku province of Indonesia, is a small volcanic island characterized by steep coastal gradients and sediment variation resulting from volcanic activity. Ternate Island is approximately 10.201,262 ha with a coastline length of 45,526 km and is inhabited by 196,130 people [7], [8]. The island is situated in an area of active tectonic movement, leading to unique sediment composition along its coastlines. One ecosystem in this island's intertidal zone is the seagrass ecosystem. The vital role of seagrass along the coast of Ternate Island requires investigation because of its different characteristics related to the distribution and condition of the substrate. This study aims to assess the relationship between sediment fraction characteristics and seagrass biodiversity distribution in Ternate Island, contributing to the broader understanding of seagrass-sediment interactions and their implications for ecosystem resilience and management. Seagrass adaptation to unstable substrate conditions due to the influence of volcanic materials can create extreme substrate conditions that challenge seagrass distribution [9], [10].

Understanding the characteristics of sediment fractions in seagrass meadows on volcanic islands is essential, as it is an environmental parameter affecting substrate conditions [11]. Habitat characteristics and sediment fraction composition significantly impact seagrass environments' physical and chemical properties [12], [13]. Additionally, knowledge of the properties of sediment fractions can yield valuable insights into sediment stability, nutrient cycling, and overall ecosystem health. Researchers can gain a better understanding of the factors influencing seagrass growth and production by assessing sediment parameters such as particle size distribution and organic content [14], [15], [16] The sedimentary fraction of volcanic islands is significant for predicting the health and resilience of seagrass ecosystems in response to environmental changes, thus aiding in the development of optimal seagrass management strategies [17], [18], [19].

This research can contribute to advancing knowledge, especially in the context of conservation and sustainable management of seagrass on small islands. Future research focusing on assessing sediment fractions and seagrass distribution patterns is a research gap that requires accurate solutions in studying biodiversity. This study emphasizes the importance of understanding the complex relationship between sediment characteristics and seagrass ecosystems that are always influenced by ocean dynamics. Seagrass is very important in maintaining the function of ecological entities in coastal areas and small islands. The stability of seagrass ecosystems has a role in interconnectivity relationships with coral reef ecosystems and mangrove ecosystems. This research is an important reference for seagrass ecosystem research conducted in the environment of small volcanic islands, which aims to preserve biodiversity and conservation.

Materials and Methods

Study site

This research was conducted in March 2023 at four sites along the coast of Ternate Island: Kastela Beach, Jambula Beach, Falajawa Beach, and Nukila Beach. These sites were selected based on variations in sediment composition and anthropogenic influence. Sampling stations were established along transects extending perpendicular to the shoreline and divided into three zones:
- Zone 1: Nearshore, characterized by fine sediments and higher nutrient availability.
- Zone 2: Mid-zone exhibiting mixed sediment composition and moderate exposure to hydrodynamic forces.
- Zone 3: Offshore, adjacent to coral reef environments with coarser sediments and stronger currents.

Each of the four sampling locations has unique characteristics. Site 1 at Kastela Beach, with coordinates 127°18'27.70"E, 0°45'47.37"N, is a beach area adjacent to local tourist attractions and sparsely populated settlements, featuring semi-closed water conditions due to natural barriers. Site 2 at Jambula Beach, with coordinates 127°19'4.00"E, 0°45'23.19"N, is located near the

Pertamina oil port and has a relatively dense settlement, indicating semi-closed water conditions due to natural obstacles. Site 3 at Falajawa Beach, with coordinates 127°23'19.27"E, 0°47'5.25"N, consists of a reclaimed beach area close to a very dense residential area characterized by relatively open water conditions. Site 4 at Nukila Beach, with coordinates 127°23'25.22"E, 0°47'15.03"N, is a reclaimed beach that has been developed into a local tourist location and is near a densely populated residential area, indicating open water conditions (Fig. 1).
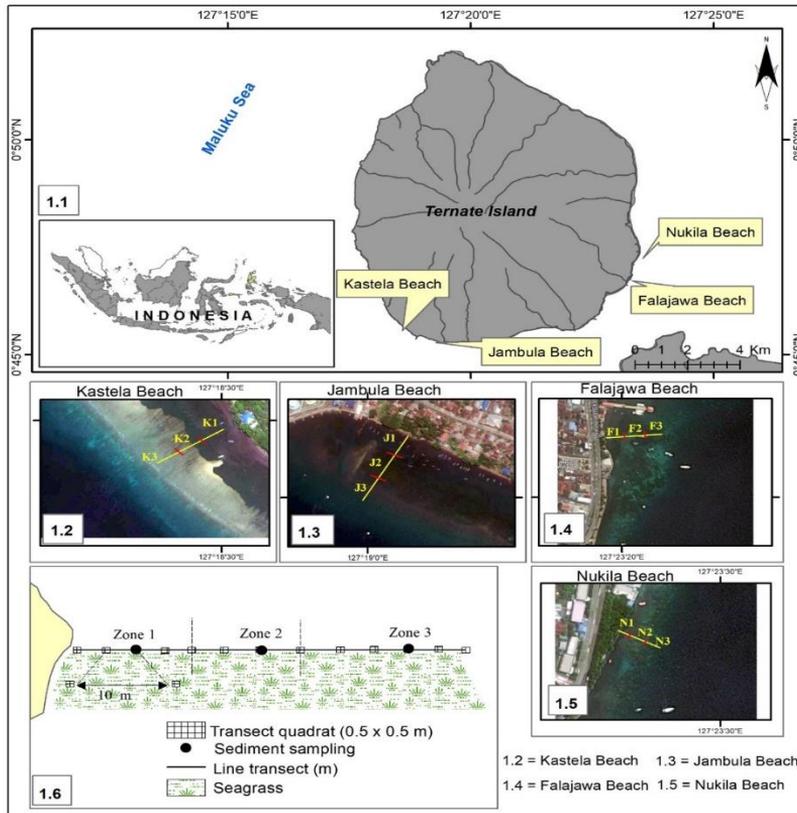

Fig. 1. Map of the research location on Ternate Island

Data collection

Seagrass Community Assessment

Data collection for seagrass distribution in this study was carried out at four sampling sites using transects adjusted to the seagrass distribution's width. The transect line is divided into three segments designated as distribution zones. Site 1 is represented by zones K1, K2, and K3; Site 2 is represented by zones J1, J2, and J3; Site 3 is represented by zones F1, F2, and F3; and Site 4 is represented by zones N1, N2, and N3. The distribution of seagrass and biodiversity was assessed using square sampling along perpendicular transects from the coastline. Squares (0.5×0.5 m) are systematically placed at 10-meter intervals along each transect. The following parameters are noted:

- The species identification process for collecting seagrass species data in each square uses a seagrass identification guidebook [20], [21].
- Abundance, where data collection is carried out based on the number of stands of each type, which is then converted to the number of individuals per square meter [22], [23].

- The closing percentage where data collection is done is based on visual estimation in squares [21].
- Diversity index: Shannon-Wiener Index (H'), Evenness Index (E), and Simpson Dominance Index (D) [24].

Sediment Sampling and Analysis

Sediment samples were collected using a 4-inch diameter core at each zone and extracted to a depth of 15 cm. Samples were placed in labeled bags, transported to the laboratory, and air-dried before analysis. The particle size distribution of sediment was determined using a sieve shaker, categorizing sediment into five fractions: gravel (>4.75 mm), coarse sand (0.6–2 mm), medium sand (0.25–0.425 mm), fine sand (0.075–0.15 mm), and mud (<0.075 mm) [25].

Data analyses

Seagrass Community Analysis

The collected data were analyzed using ecological indices:

- Abundance and coverage were calculated as indicators of seagrass distribution

Abundance is critical for assessing ecosystem stability and is an indicator of species distribution conditions. Seagrass abundance is calculated based on the density of individual seagrass stands across a specific area (m²).

$$\text{Abundance} = \frac{\text{Number of individuals of all seagrass species in the quadrat}}{\text{Transect area (m)}^2}$$

Seagrass cover analysis was carried out visually using the sum of the percentage of seagrass leaf cover in the box [21]. The seagrass cover in this study was analyzed based on the type of seagrass found in each square transect area.

- Diversity, evenness, and dominance indices provided insights into the community structure [23].

Diversity is a key measure of biodiversity that can be utilized to assess the ecological balance within a specific habitat. This study analyzes the diversity of seagrass communities using the Shannon-Wiener index (H').

$$H' = (pi \ln pi), pi \text{ defined as } \frac{ni}{N}$$

where: H': Shannon-Wiener Diversity Index of seagrasses; ni: Number of individuals of species I; N: Total of all seagrass individuals of all species.

Uniformity serves as a measure of community uniformity, which can be utilized to evaluate an ecosystem's resilience and equilibrium based on the Uniformity Index (E). The value of E ranges from 0 to 1, with higher E values indicating greater community uniformity within an ecosystem, thereby enhancing its stability in the face of external disturbances.

$$E = \frac{H'}{Hmax}$$

where: E: Seagrass Uniformity Index; H': Seagrass Diversity Index; Hmax: Maximum of Seagrass Diversity Index.

The dominance value is an indicator of an ecosystem's stability. It can be derived from Simpson's Dominance Index (D), which ranges from 0 to 1. A high dominance value indicates ecological imbalance.

$$D = \sum_{i=1}^{s} pi^2 = \sum_{i=1}^{s} \left[\frac{ni}{N}\right]^2$$

where: D: Dominance Index; ni: Number of individuals of species I; N: Total number of individuals of all species; pi: Proportion of individuals of species I; s: Number of seagrass species found.

Statistical and Multivariate Analysis

This quantitative research consists of several parameters, so statistical analysis and multivariate analysis are needed for data processing. The types of analysis used include Pearson Correlation analysis, Principal Component Analysis (PCA), and Agglomerative Hierarchical Clustering (AHC) analysis. Pearson Correlation Analysis was used to examine the relationship between sediment composition and seagrass parameters. PCA analysis was used to identify the main sediment variables that affect seagrass distribution. AHC analysis is used to classify the grouped zones based on the similarity of sediment fractions.

Results and discussion

Seagrass Biodiversity and Distribution Patterns

The results of the study found seven species of seagrass in all research locations, namely *Enhalus acoroides, Thalassia hemprichii, Cymodocea rotundata, Cymodocea serrulata, Syringodium isoetifolium, Halophila ovalis,* and *Halodule pinifolia*. The distribution of seagrass species based on zone division on Ternate Island found different information (Fig. 2).
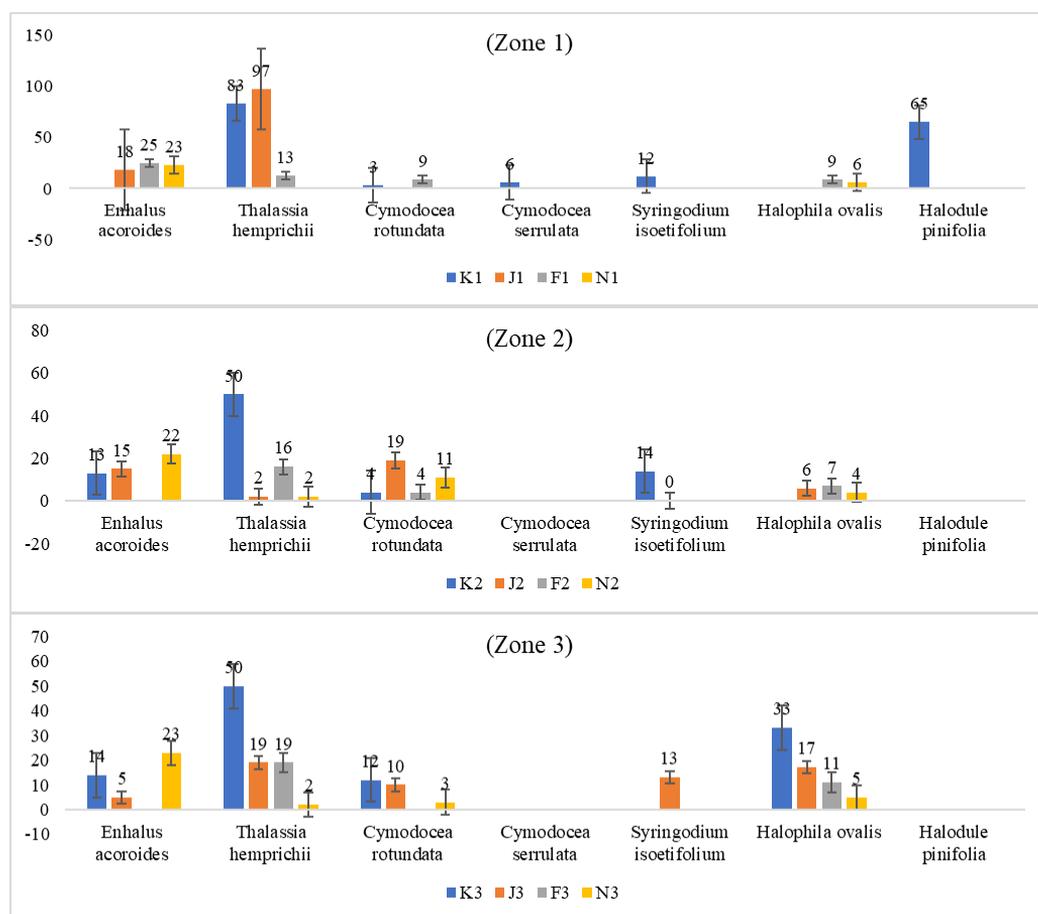

Fig. 2. Average distribution of species types and individual counts of seagrass found on Ternate Island, presented within vertical zone segmentation: (a) Zone 1, (b) Zone 2, (c) Zone 3.

The distribution of seagrass based on zoning division found the number of species and the number of individuals with relatively different values (Fig. 2). In Zone 1, seven species of seagrass

were identified, namely *Enhalus acoroides, Thalassia hemprichii, Cymodocea rotundata, Cymodocea serrulate, Syringodium isoetifolium, Halophila ovalis,* and *Halodule pinifolia*. In Zones 2 and 3, the same five species of seagrass were identified, namely *Enhalus acoroides, Thalassia hemprichii, Cymodocea rotundata, Syringodium isoetifolium,* and *Halophila ovalis*. These results show that the number of seagrass species in the nearshore zone is higher than in the mid-zone and offshore zones. The number of seagrass species found in zone 1 is relatively higher than the number of seagrass species found in zones 2 and 3. The average number of seagrass individuals found in the nearshore zone shows a declining pattern in the mid-zone and offshore zone. The variation in the number of species and the number of associated seagrass individuals is influenced by the environmental characteristics of the habitat [26], [27], [28], [29].

Several seagrass species are consistently found in all zone divisions with relatively different numbers of individuals. The types of seagrass found to be consistent in all zone divisions are *Enhalus acoroides, Thalassia hemprichii, Syringodium isoetifolium,* and *Halophila ovalis*. The difference in species richness and the number of seagrass individuals in each study zone can be attributed to the varied environmental characteristics [30], [31]. Certain seagrass species in all zones show resilience and adaptability [30], [32]. Generally, larger seagrass species show a higher ability to adapt to less stable habitat environments [30], [33]. In contrast, smaller seagrass species tend to be more susceptible to fluctuating and extreme environmental conditions [34].

The richness of species tends to be proportional to the seagrass cover found in the zone division. The percentage of seagrass coverage based on zoning division at each station shows a pattern of decreasing average values. The highest percentage of seagrass cover was found in Zone 1 (75% cover), followed by Zone 2 (50% cover). The lowest percentage of seagrass cover was found in Zone 3 (43% cover) (Fig. 3). These trends suggest that sediment stability and nutrient availability play an important role in supporting seagrass growth.
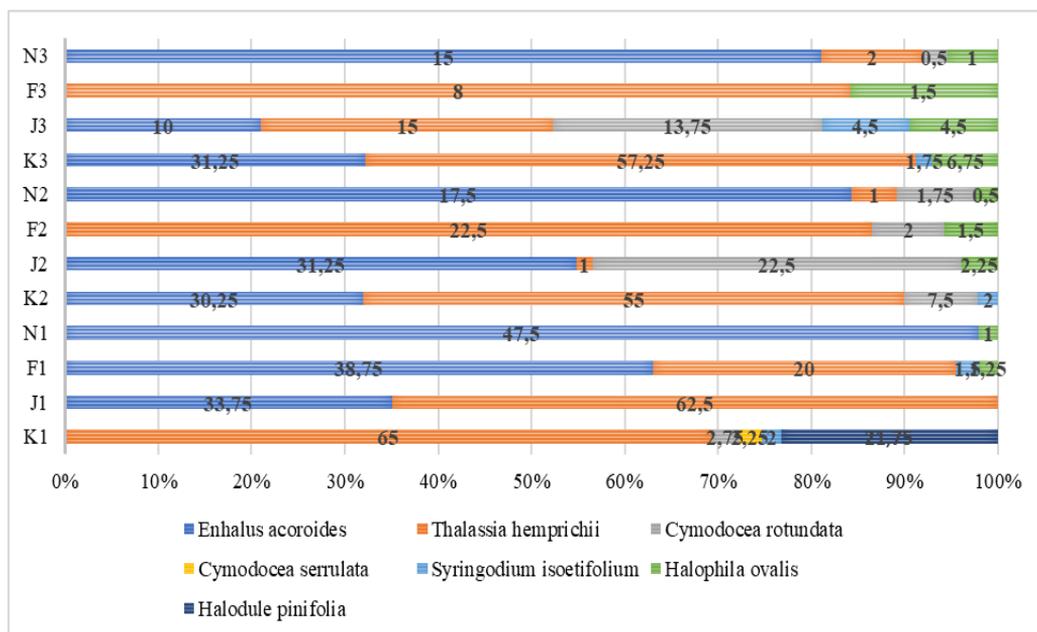

Fig. 3. Percentage of seagrass coverage on Ternate Island presented in a vertical zone segmentation

Higher seagrass cover in zones 1 and 2 is due to a higher density of individuals [35] In addition, the high percentage of seagrass cover in zones 1 and 2 is also due to the dominance of larger seagrass species found in this area [36], [37]. In contrast, Zone 3 obtains a lower percentage of seagrass cover because in this zone the density of seagrass individuals is rare and many seagrass

species are small species [38]. In general, the distribution of biodiversity and seagrass cover at the research sampling location on Ternate Island is closely related to the location of the zone. Zone 1, as a nearshore zone, is located closer to the mainland so that it receives a higher nutrient overflow [39], while zone 3, adjacent to coral reefs, is a zone that has lower nutrient availability [40]. Zone 3 is an off-coast zone adjacent to coral reefs known as oligotrophic waters [41].

The characteristics of the type of seagrass research sampling location on Ternate Island significantly affect the distribution of seagrass species and cover. Stations 1 and 2 show a high percentage of cover because the characteristics of aquatic habitats between the two have a high similarity. The topographic features of these two locations are flat areas with semi-closed water types because barrier corals protect them. The type of protected beach significantly affects the increase in the percentage of seagrass cover [42]. In contrast, the lower percentage of seagrass cover observed at stations 3 and 4 is due to the type of sloping topography and the relatively more open type of coastal waters. Coastal conditions and open waters are more susceptible to oceanographic dynamics, especially currents and waves [43], [44]. Currents and wave action can negatively impact the physical dimensions of seagrass and disrupt the substrate's stability, affecting the availability of nutrients in seagrass [45].

Seagrass Biodiversity Community Structure

The seagrass community structure analyzed in this study includes abundance, diversity, uniformity, and dominance (Table 1). The structure of seagrass communities is fundamental to be revealed in the study of seagrass distribution on Ternate Island to measure the ecological dynamics, function, and environmental stability of seagrass ecosystem habitats. A comprehensive study of the seagrass community structure was carried out to provide a comprehensive overview of the interaction between species and ecosystem response to changes in seagrass habitat on Ternate Island, which is affected by volcanic and anthropogenic activities.

Table 1. The ecological value of the seagrass community structure in Ternate Island is presented in vertical zone segmentation

(Zone)	Transect Segmentation	Abundance	Diversity	Uniformity	Dominance
Zone 1	K1	169	1.58	0.53	0.4
	J1	115	0.63	0.21	0.74
	F1	56	1.86	0.62	0.3
	N1	29	0.74	0.25	0.67
	Average	92	1.20	0.40	0.53
Zone 2	K2	81	1.51	0.5	0.44
	J2	42	1.66	0.55	0.35
	F2	27	1.36	0.45	0.44
	N2	39	1.75	0.51	0.41
	Average	47	1.57	0.50	0.41
Zone 3	K3	109	1.77	0.59	0.33
	J3	30	0.95	0.32	0.54
	F3	30	0.95	0.32	0.54
	N3	33	1.34	0.45	0.52
	Average	51	1.25	0.42	0.48

The structure of seagrass communities based on the average value of the ecological index in the zoning division area obtained varying quantitative values (Table 2). Seagrass abundance from all zones had different average values, namely in zone 1 with a total of 92 individuals, zone 2 with a total of 47 individuals, and zone 3 with a total of 51 individuals. This study's high and low seagrass abundance correlates with the number of individuals in the square unit. A comparison of the results of the analysis of the abundance value shows that the seagrass ecosystem in Zone 1 shows the most stable indicators from Zones 2 and 3. The abundance value of seagrass can be affected by the sum of individual density measures of the seagrass species [38]. The Diversity score based on zone division was obtained in zone 1 with a value of 1.20, zone 2

with a value of 1.57, and zone 3 with a value of 1.25. Diversity in all zones is classified as moderate, indicating moderate species diversity, reflecting the balance of seagrass species in the ecosystem [46], [47]. Based on the uniformity value in Zone 1 and Zone 3, the community structure, with values of 0.40 and 0.42, can be classified in the low category. The community structure in zone 2, with an average score of 0.50, is classified as moderate. This condition illustrates that uniformity with medium and low categories indicates the existence of seagrass species that dominate where there are small seagrass species [48]. The structure of the seagrass community based on the value of dominance was obtained by two groups, namely the medium and low categories. Seagrass dominance with a medium category was found in zone 1 with a value of 0.52; a low category was found in zones 2 and 3 with values of 0.41 and 0.48, respectively. The dominant value of seagrass with a medium category indicates that there are seagrass species that contribute more but do not dominate the population significantly [46]. The dominance value of seagrass with a low category describes the structure of the ecosystem community that is still balanced and illustrates that no one type of seagrass dominates in the ecosystem [30], [49].

Sediment Composition and Zonal Variation

The sediment distribution based on zone division shows the average composition of the sum of the weight percentages of different fractions in each zone (Table 3). The composition of the weight percentage of the sediment fraction in zone 1 was obtained with an average value of gravel at 4.13%, coarse sand at 9.59%, medium sand at 46.56%, fine sand at 20.55%, and mud at 19.17%.

Tabel 3. Distribusi fraksi sedimen di area lamun berdasarkan pembagian zona di Pulau Ternate

Zona	Transect Segmentation	Sediment Fraction (%)				
		gravel	coarse sand	medium sand	fine sand	mud
Zona 1	K1	3.76	9.70	44.41	19.91	22.22
	J1	2.61	8.45	29.01	27.22	32.72
	F1	1.22	8.40	35.21	33.41	21.76
	N1	8.92	11.83	77.60	1.64	0.00
	Average	4.13	9.59	46.56	20.55	19.17
Zona 2	K2	7.11	21.85	60.19	5.23	5.62
	F2	3.76	9.46	53.03	28.08	5.68
	J2	0.18	2.39	25.54	42.49	29.41
	N2	6.98	8.26	48.61	30.76	5.39
	Average	4.51	10.49	46.84	26.64	11.52
Zona 3	K3	0.67	12.65	81.38	5.23	0.07
	J3	4.82	6.41	54.95	33.14	0.68
	F3	5.12	21.71	46.13	19.16	7.89
	N3	3.03	10.38	60.00	26.41	0.18
	Average	3.41	12.78	60.62	20.99	2.20

The composition of the weight percentage of the sediment fraction in zone 2 was obtained with an average value of gravel at 4.51%, coarse sand at 10.49%, medium sand at 46.84%, fine sand at 26.64%, and mud at 11.52%. The composition of the weight percentage of the sediment fraction in zone 3 was obtained with an average value of gravel at 3.41%, coarse sand at 12.78%, medium sand at 60.62%, fine sand at 20.99%, and mud at 2.20%. The most dominant type of sediment fraction in all zones is medium sand, with an average range of 46.56% to 60.62%. Based on the sediment fraction distribution, it was found that sediments with a medium sand size relative to them were found to be the most dominant in all zones. Coarse-sized sedimentary fractions (gravel and coarse sand) are found in relatively small campuses. Zones that are heavily influenced by hydrodynamic variations are characterized by coarser sediment fractions [50], [51], [52].

The composition of the sediments was found to vary significantly across the study zones. The sedimentary fraction in Zone 1 is primarily fine sand and mud, which supports higher

abundance and diversity of seagrass. The sedimentary fraction in Zone 2 is a mixture of medium sand and fine sediment that causes the diversity of seagrass in the medium category. The sediment fraction in Zone 3 is dominated by medium and coarse sand, which correlates with reduced seagrass cover. The presence of coarser sediments in offshore zones likely contributes to lower seagrass density due to increased hydrodynamic forces affecting substrate stability [25], [53], [54], [55].

Correlation Between Sediment and Seagrass Variables

In this study, the influence of sediment fraction on the distribution of seagrass on Ternate Island is explained through the analysis of correlation relationships. The variables were analyzed using the Pearson correlation between the sediment fraction composition and the seagrass ecological conditions' parameters (Table 4). The composition of the sediment fraction consists of 5 variables: gravel, coarse sand, medium sand, fine sand, and mud. The seagrass ecological conditions analyzed consisted of 6 variables: number of species, cover percentage, abundance, diversity, uniformity, and dominance.

Table 4. Correlation matrix (Pearson) relationship analysis between variables

Variables	Number of species	Cover Percentage	Abundance	Diversity	Uniformity	Dominance	…	Mud
Number of species	1	0.998	0.998	-0.605	-0.635	0.791	…	0.836
Cover Percentage	0.998	1	0.991	-0.548	-0.580	0.747	…	0.872
Abundance	0.998	0.991	1	-0.655	-0.684	0.829	…	0.799
Diversity	-0.605	-0.548	-0.655	1	0.999	-0.965	…	-0.069
Uniformity	-0.635	-0.580	-0.684	0.999	1	-0.975	…	-0.108
Dominance	0.791	0.747	0.829	-0.965	-0.975	1	…	0.326
Gravel	0.177	0.245	0.113	0.677*	0.648*	-0.462	…	0.688
Coarse sand	-0.716*	-0.763**	-0.670*	-0.122	-0.084	-0.140	…	-0.982
Medium sand	-0.515*	-0.573*	-0.459	-0.371	-0.335	0.116	…	-0.901
Fine sand	-0.555*	-0.496	-0.608*	0.998**	0.995**	-0.948**	…	-0.008
Mud	0.836**	0.872**	0.799**	-0.069	-0.108	0.326	…	1

Note : ** = very strong (0.75 – 1); * = strong (0.5-0.75); moderate (0.25-0.5); weak (0 – 0.25)

■ = positive very strong;   ■ = positive strong;   ■ = Negative very strong;   ■ = negative strong

The results of the analysis of sediment fraction with ecological conditions found a robust positive correlation between fine sand and diversity and uniformity. A robust positive correlation was also found in mud with the number of species, cover percentage, and seagrass abundance. Mud substrates for seagrass ecosystems increase diversity, uniformity, species count, cover percentage, and abundance due to their high organic matter content, strongly supporting seagrass growth [56]. The dominant substrate conditions of fine sand and mud play an important role in maintaining the stability and productivity of seagrass ecosystems, thereby creating a habitat rich in biodiversity [12], [57]. The relationship between sediment fraction and seagrass ecological conditions strongly influenced gravel diversity and uniformity. Gravel has a strong correlation with diversity and uniformity because it can create a stable substrate environment that supports the diversity and uniformity of seagrass. Gravel that has high porosity characteristics and better substrate stability than mud or fine sand can create ideal conditions for seagrass to be more diverse and more evenly distributed in the ecosystem [58], [59].

The influence of sediment fraction with the distribution of seagrass ecological conditions found a robust negative correlation between coarse sand on cover percentage and fine sand on

dominance. The negative correlation between coarse sand and seagrass cover percentage impacts the inhibition of seagrass growth and spread caused by sediment instability and low nutrient content [60], [61]. The robust negative correlation between fine sand supports species diversity and reduces certain types of seagrass dominance. The relationship between the sediment fraction variable and the seagrass ecological condition in this study was also found to be a strong negative correlation, namely coarse sand with several species and abundance, medium sand with several species and cover percentage, and fine sand with several species and abundance. This study shows that the coarser or finer the sediment correlates with the low diversity and abundance of seagrass. Coarse sand is the type of sediment fraction that plays the biggest role in inhibiting the development of seagrass because it causes substrate instability and low nutrients [15], [62], [63].

Based on Principal Component Analysis (PCA) results, sediment characteristics showed that fine sand and mud were the main drivers of seagrass biodiversity. In contrast, coarser sediments acted as limiting factors. Fine sand is a characteristic of seagrass biodiversity found in zone 2, while mud is a characteristic found in zone 1. Coarser sediments were found to be a characterizer of seagrass distributed in zone 3 (Fig. 4).

Implications for Conservation and Management

The characteristics of seagrass ecosystem distribution are essential to study to understand the dynamics of seagrass ecosystems, maintain the sustainability of seagrass resources, and develop effective seagrass conservation strategies [9], [45], [62], [64]. Analysis of sediment parameters and seagrass ecosystem conditions using Agglomerative Hierarchical Clustering (AHC) and Principal Component Analysis (PCA) found seagrass biodiversity characteristics on Ternate Island.

The AHC analysis of the seagrass distribution in this study identified the dendrogram grouping of seagrass distribution zones based on the condition of the sediment fraction. At a similarity value of 0.881, a grouping of two dendrograms representing two groups of seagrass distribution was obtained. Group one consists of zone 1 with a sedimentary character that is finer and muddier. Group two consists of a combination of zone 2 and zone 3 with a coarser sedimentary character. The similarity value of 0.973 shows three groups of dendrograms that display each of the characteristics of zone 1, zone 2, and zone 3. The high similarity of AHC dendrogram values presents an opportunity for sustainable conservation of seagrass resources [65], [66].

The PCA analysis in this study obtained very good derived eigenvalues using two axes, namely F1 (57.10%) and F2 (42.90%) (Fig. 4). The PCA analysis in this study succeeded in identifying the parameters that determine seagrass distribution based on zone division. The characteristics of seagrass distribution based on the variables analyzed in this study were successfully reduced to four groups. Group one is zone 1 with character variables including number of species, cover percentage, abundance, and dominance. The second group is zone 2 with character variables including diversity, uniformity, and fine sand. The third group is zone 3 with the variables of coarse sand and medium sand characters. Group 4 is a variable that does not characterize one of the zones consisting of gravel and mud. Gravel and mud are found distributed throughout the zone but are relatively small in number. The variable characteristics that characterize the distribution of seagrass are very helpful in seagrass conservation and sustainable management [65], [66].

This study highlights the importance of sediment stability in maintaining seagrass ecosystems. Seagrass conservation strategies should focus on three important things recommended from the results of this study. Conserving nearshore habitats with high levels of fine sand and mud to support biodiversity. Apply sediment management to mitigate seagrass ecosystems on volcanic islets and anthropogenic disturbances affecting substrate composition. Monitor hydrodynamic changes that affect sediment deposition and erosion patterns.
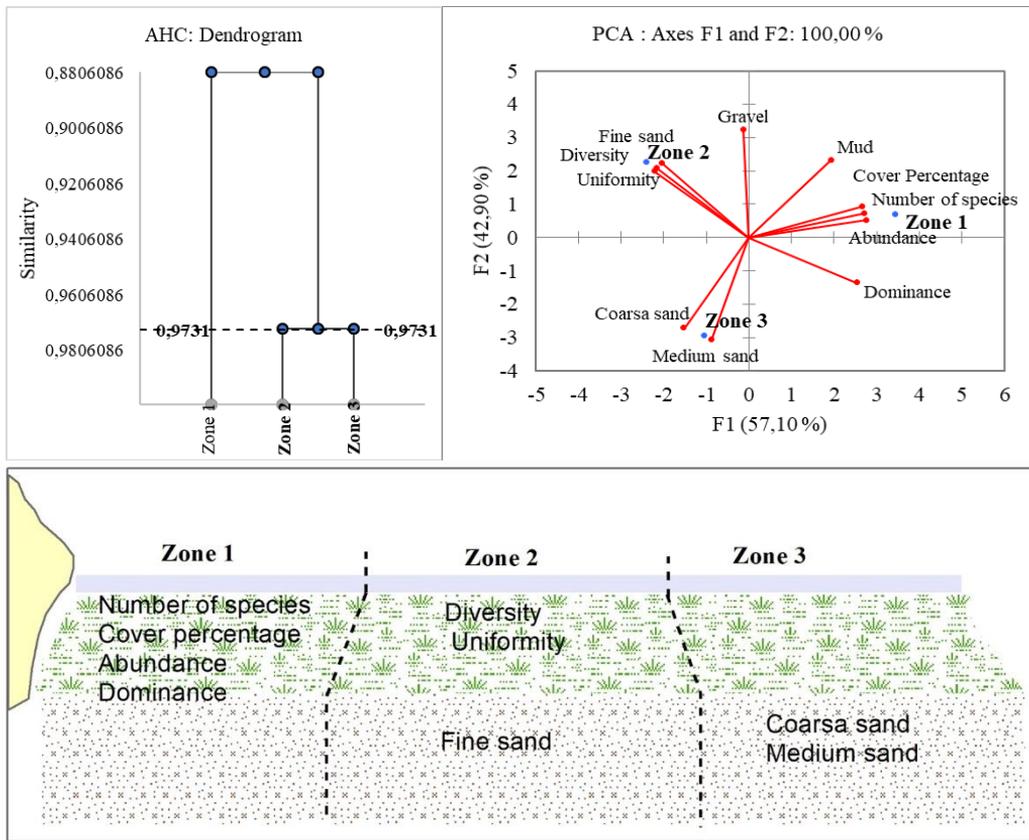
Fig. 4. Results of AHC and PCA analyses, and zoning of seagrass distribution on Ternate Island

Conclusions

This study demonstrates that sediment fraction characteristics play a crucial role in shaping seagrass biodiversity distribution on volcanic islands. Fine sand and mud fractions promote higher species richness and coverage, whereas medium and coarse sand negatively impact seagrass density. These findings provide valuable insights into seagrass-sediment interactions, supporting the development of targeted conservation and management strategies. Future research should focus on long-term monitoring and the integration of hydrodynamic modeling to enhance the understanding of sediment dynamics and seagrass resilience in volcanic coastal ecosystems.

Acknowledgments

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