Jurnal Ilmu dan Teknologi Kelautan Tropis
p-ISSN: 2087-9423
e-ISSN: 2620-309X

Check for updates

OPEN ACCESS

Article Info:
Received 29 March 2026
Revised 19 July 2026
Accepted 31 August 2026

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Characteristics of Sediment Grain Size in Shallow Waters of Kapota Island and Atoll, Wakatobi

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Abstract

Shallow waters in tropical island and atoll regions are highly dynamic environments where sediment grain size characteristics and distribution are influenced by complex interactions. This study aims to characterize shallow-water sediments on Kapota Island and Kapota Atoll, Wakatobi. Sediment samples were collected using a core pipe at 14 observation stations representing both locations. Sediment grain size analysis was performed using the dry sieving method, while the fraction composition, sediment texture, and statistical parameters were determined with the aid of Gradistat software. The results show that the shallow water sediments at both locations are composed of three main fractions: gravel (1.20–44.55%), sand (54.91–98.21%), and silt (0.01–10.50%). Texturally, sediments are classified into four types: sandy gravel, gravelly sand, slightly gravelly sand, and slightly gravelly muddy sand. The statistical parameter values indicate a mean grain size range from very coarse to very fine sand, a sorting level from moderately sorted to very poorly sorted, a skewness value from symmetrical to strongly skewed toward the coarse fraction, and a kurtosis from very platykurtic to extremely leptokurtic. The Mann–Whitney U test showed no significant differences between Kapota Island and Kapota Atoll in mean grain size, sorting, skewness, or kurtosis ($p > 0.05$). However, spatial heterogeneity was observed among sampling stations. These findings indicate broadly comparable sediment characteristics between the two settings, while local variations reflect differences in sedimentary conditions. The results provide baseline information for shallow-water sediment characterization and support future coastal monitoring and management in Wakatobi National Park.

Keywords: Gradistat, grain size, granulometry, sediment texture, statistical parameters

1. Introduction

Sediment is made up of particles that come from different organic and inorganic materials and settle on the bottom of shallow or deep-sea waters. These particles can be different sizes and shapes (Setiawan et al., 2019; Ma'arif and Hidayah, 2020). Characterizing sediment grain size is essential, as it elucidates the mechanisms of sediment transport and deposition directly associated with hydrodynamic dynamics, including currents, waves, and tides in shallow water environments (Nugroho and Basit, 2014; Liang et al., 2020; Bainbridge et al., 2021). The size of the sediment grains has a big effect on how the sediment reacts to the things that affect its distribution. Compared to larger sediments, smaller sediments will spread out more from where they started and take longer to settle.

Information about underwater conditions, especially the characteristics and distribution of sediments on the seabed, is essential to know, especially for planning development in coastal areas (Rachman et al., 2021; Pasaribu et al., 2021; Umehara et al., 2023). Additionally, sediment grain size analysis is very useful for identifying sediment types on the seafloor surface (Setiawan et al., 2019; Liang et al., 2020; Bainbridge et al., 2021; Roem et al., 2021; Muhardi et al., 2021; Rachman et al., 2023; Wang et al., 2023) as well as for understanding the conditions and energy dynamics in sediment deposition environments and the processes that occur during deposition (Bainbridge et al., 2021; Mutaqin et al., 2024). The determination of sediment classification has helped geologists obtain an overview and information about processes in a body of water that occurred in the past (Tucker, 2001). Specifically, the analysis of sediment grain size can be used as a method to determine the distribution and spatial changes in sediment conditions on a waterbed, where the distribution and irregularities can serve as indicators to understand the characteristics of sediment flow in a water body (Stevenson et al., 2014; Nugroho and Basit, 2014; Cabezas-Rabadán et al., 2021).

Sediment deposition in coastal areas is more complex because sediments are highly dynamic spatially and temporally (Nugroho and Information about underwater conditions, especially the characteristics and distribution of sediments on the seabed, is essential to know, especially for planning development in coastal areas Basit, 2014). This phenomenon is influenced by various forms of sediment transport processes, such as saltation, traction, and suspension (Umar et al., 2020), as well as the tidal processes of seawater (Putra and Nugroho, 2017), which together affect how sediments are distributed and deposited in coastal environments, leading to variations in sediment composition and ecological impacts in these areas. Although Kapota Island and Kapota Atoll are located within the same marine region of Wakatobi National Park, they represent two contrasting shallow-water geomorphological systems. Kapota Island is a fringing reef island influenced by adjacent coastal processes, whereas Kapota Atoll is an isolated reef platform with an exposed outer reef and a relatively sheltered inner lagoon. These differences are expected to produce distinct hydrodynamic conditions and sedimentary environments, resulting in variations in sediment grain-size distribution and texture. Previous studies in the Wakatobi region have mainly focused on benthic habitat distribution and reef environments, whereas comparative characterization of sediment grain-size properties between Kapota Island and Kapota Atoll remains limited. This study therefore addresses whether the contrasting geomorphological and benthic settings of these two systems are reflected in differences in sediment grain-size composition, texture, and statistical parameters. Therefore, this study aims to characterize and compare the grain-size composition, sediment texture, and statistical grain-size parameters of shallow-water sediments from Kapota Island and Kapota Atoll. The study further uses cluster analysis to identify similarities and differences in sediment characteristics among sampling stations, providing insight into how sediment sources, benthic habitat characteristics, and depositional settings may contribute to spatial variability in shallow-water sediments within Wakatobi National Park.

2. Materials and Methods

2.1. Study Time and Location

This study was conducted in the waters of Wakatobi Regency, Southeast Sulawesi (**Figure 1**). Wakatobi Regency waters are one of the national parks in Indonesia that are formed based on the Decree of the Minister of Forestry No. 7651/Kpts-II/2002. The majority of the Wakatobi National Park area is marine waters (97%), while the land area is just 3% (Balai Taman Nasional Wakatobi, 2020). Wakatobi National Park is rich in marine natural resources (Nababan et al., 2021; Hafizt et al., 2021; Hasan et al., 2022; Hamuna et al., 2023, 2024) including typical reef-like coral ecosystems in tropical regions, such as fringing reef, barrier reef, and atoll (Balai Taman Nasional Wakatobi, 2020).

Sediment samples were taken at two different locations, namely Kapota Island and Kapota Atoll, with 7 sampling stations each (**Figures 1b–1d**). The sampling stations were distributed to represent the spatial variation of shallow-water sediment characteristics within each study area. At Kapota Atoll, five stations (A1–A5) were located in the southern part of the atoll, whereas two stations (A6–A7) were located in the northern part. At Kapota Island, the seven stations (P1–P7) were distributed along the eastern coastal waters facing Wangi-Wangi Island. The station distribution was determined based on the accessibility of the shallow-water areas and to capture spatial variation in sediment characteristics within the two study areas. Sampling was conducted on 6 April 2023 at Kapota Atoll and on 9 April 2023 at Kapota Island. The sampling dates differed because the two study areas are spatially separated, and field activities were adjusted to local sea conditions, particularly relatively high wave conditions that affected the safety and accessibility of the sampling sites. The geographic coordinates and water depth of each sampling station are presented in **Table 1** to provide the spatial and bathymetric context of the sediment samples.

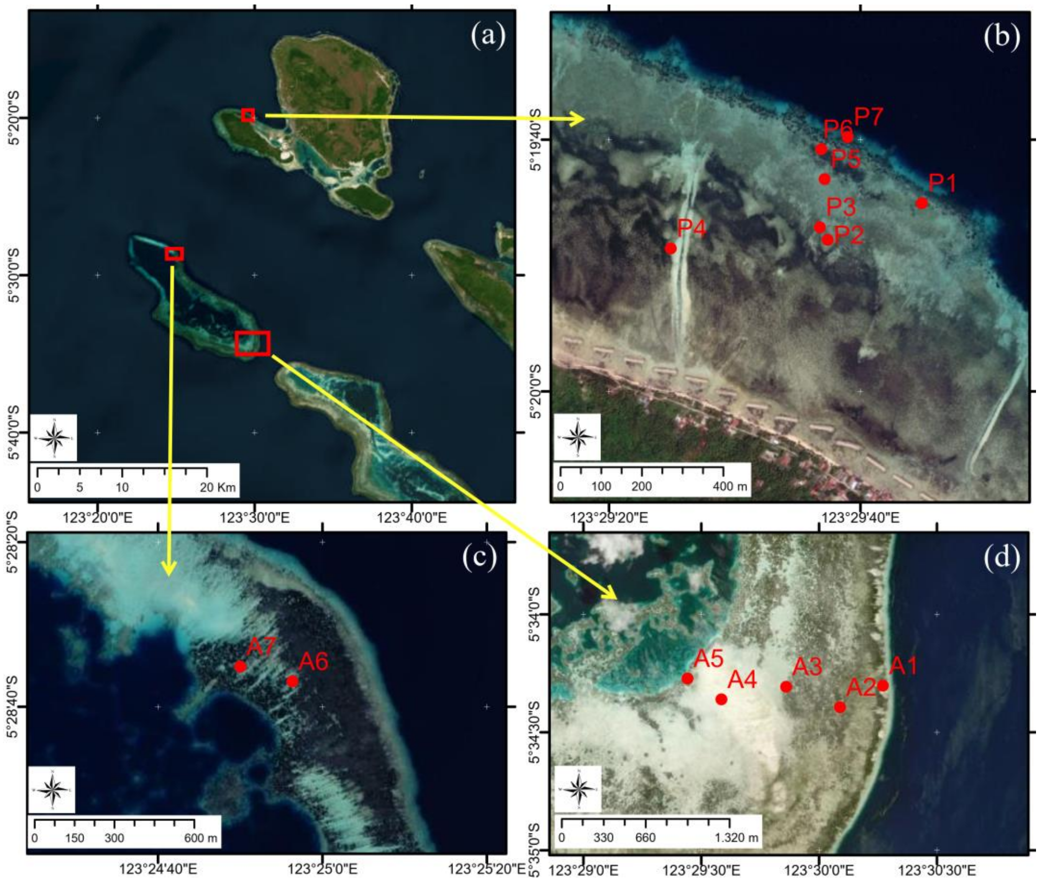

Figure 1. (a) Map of shallow water sediment sampling locations in Wakatobi waters, Southeast Sulawesi, Indonesia; (b) Seven stations on Kapota Island; (c) Two stations in the northern part of Kapota Atoll; and (d) five stations in the southern part of Kapota Atoll. P1–P7 are sampling points on Kapota Island and A1–A7 on Kapota Atoll.

Table 1. Sampling stations, geographic coordinates, and water depth for sediment collection in Kapota Atoll and Kapota Island.

Stations	Location	Longitude	Latitude	Water depth (m)
A1	Kapota Atoll	123°30'16.25"E	5°34'18.08"S	2.7
A2	Kapota Atoll	123°30'5.32"E	5°34'23.56"S	1.1
A3	Kapota Atoll	123°29'51.62"E	5°34'18.31"S	0.8
A4	Kapota Atoll	123°29'35.12"E	5°34'21.58"S	0.9
A5	Kapota Atoll	123°29'26.48"E	5°34'16.23"S	2.4
A6	Kapota Atoll	123°24'56.34"E	5°28'36.89"S	1.7
A7	Kapota Atoll	123°24'50.03"E	5°28'35.08"S	1.9
P1	Kapota Island	123°29'44.89"E	5°19'45.02"S	3.1
P2	Kapota Island	123°29'37.40"E	5°19'47.95"S	1.4
P3	Kapota Island	123°29'36.77"E	5°19'46.92"S	1.6
P4	Kapota Island	123°29'24.91"E	5°19'48.62"S	1.1
P5	Kapota Island	123°29'37.15"E	5°19'43.11"S	2.5

Stations	Location	Longitude	Latitude	Water depth (m)
P6	Kapota Island	123°29'36.88"E	5°19'40.73"S	2.8
P7	Kapota Island	123°29'38.98"E	5°19'39.76"S	3.7

2.2. Sediment Sample Collection and Preparation

Sediment samples were collected using a core constructed from a 5-inch-diameter PVC (polyvinyl chloride) pipe, which was driven approximately 20 cm into the sediment at each sampling station. Sediment samples at depths greater than 2 m were collected with the assistance of SCUBA diving equipment. The entire sediment material recovered from the approximately 20-cm core interval was treated as a single sample and thoroughly homogenized before laboratory analysis. Thus, the samples analyzed in this study represent integrated sediment from approximately 0–20 cm depth rather than surface sediment alone. This sampling approach was intended to characterize the overall grain-size composition of the sampled shallow sediment layer and was not designed to evaluate vertical variations in grain-size characteristics or recent sedimentation within the core profile. The samples were then placed in labeled sample bags according to the sampling station.

The sediment samples obtained were dried using a heating oven at 100°C until dry. After drying, 500 g of sediment from each sampling station was used for granulometric analysis using the dry-sieving method. A series of sieves with nominal mesh openings of 4.0, 2.0, 0.5, 0.25, 0.074, and 0.044 mm was used to separate the sediment into operational grain-size fractions (**Figure 2**). The sieve sequence was selected to separate the major gravel, sand, and fine-sediment fractions required for the subsequent Gradistat-based grain-size classification and statistical analysis. The relatively wide intervals between some sieve sizes, particularly 2.0–0.5 mm and 0.25–0.074 mm, were adopted as an operational fractionation scheme for the available sediment analysis and were not intended to reproduce every individual Wentworth grain-size interval. Each retained fraction was weighed and expressed as a percentage of the total dry sediment mass (Purnawan et al., 2015). The resulting grain-size fractions were subsequently entered into Gradistat for determination of sediment texture and statistical grain-size parameters.

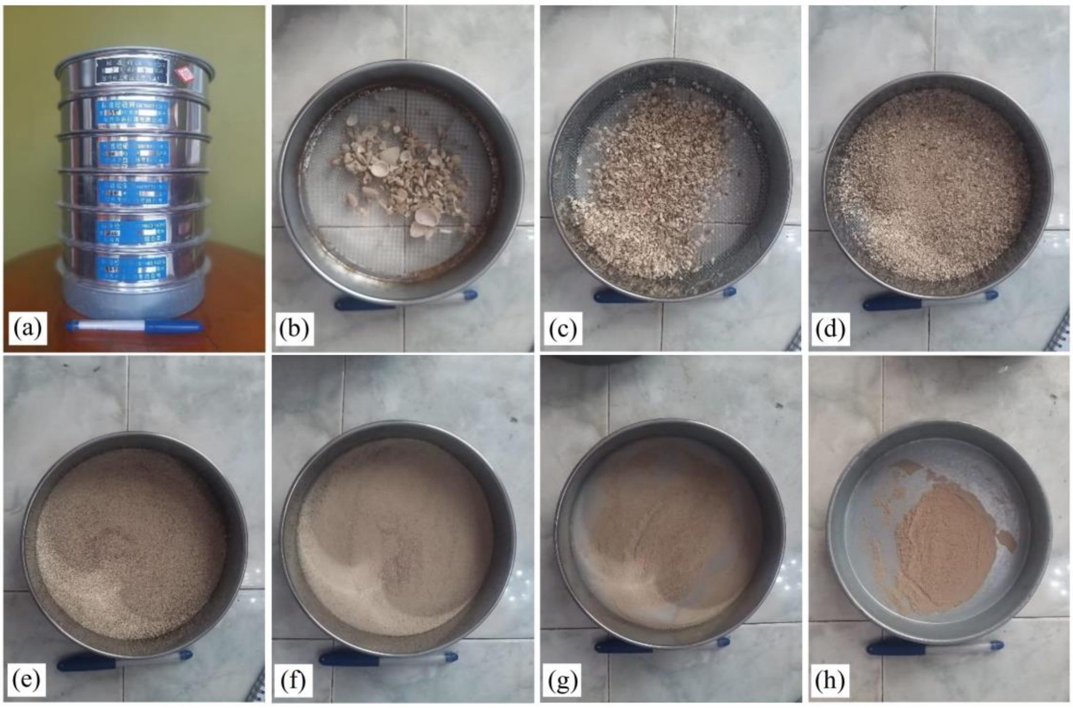

Figure 2. (a) The graduated sieve set and (b-g) examples of sediment samples retained on sieves measuring 4.0 mm, 2.0 mm, 0.5 mm, 0.25 mm, 0.074 mm, 0.044 mm and (h) the collection container. The figure illustrates the granulometric analysis procedure used to

separate sediment particles into different grain-size classes ranging from gravel to mud fractions.

2.3. Data Analysis

Blott and Pye (2001) developed the Gradistat version 9.1 software, which was used to analyze the characteristics of sediment grain sizes and the percentage of each sediment sample. The software is an alternative method for analyzing sediment characteristics (Warrier et al., 2016; Putra and Nugroho, 2017; Rachman et al., 2023), with the advantage of being much easier to use and being unlicensed or free of charge (Rachman et al., 2023). The Gradistat software can be used to determine the type and texture of sediment from the obtained sediment samples. Additionally, the software can determine the values of sediment statistical parameters, including mean grain size (M_Z), sorting (σ_I), skewness (Sk_I), and kurtosis (K_G) using several different methods, namely the Method of Moments (arithmetic, geometric, and logarithmic) and the Folk and Ward Method (geometric, logarithmic, and descriptive) (Blott and Pye, 2001). The logarithmic Folk and Ward method (Folk and Ward, 1957) is used in this study to determine the values of the four-sediment grain-size statistical parameters.

$$M_Z = \frac{\emptyset_{16} + \emptyset_{50} + \emptyset_{84}}{3} \tag{1}$$

$$\sigma_I = \frac{\emptyset_{84} - \emptyset_{16}}{4} + \frac{\emptyset_{95} - \emptyset_{5}}{6.6} \tag{3}$$

$$Sk_I = \frac{\emptyset_{16} + \emptyset_{84} - 2\emptyset_{50}}{2(\emptyset_{84} - \emptyset_{16})} + \frac{\emptyset_{5} + \emptyset_{95} - 2\emptyset_{50}}{2(\emptyset_{95} - \emptyset_{5})} \tag{3}$$

$$K_G = \frac{\emptyset_{95} - \emptyset_{5}}{2.44(\emptyset_{75} - \emptyset_{25})} \tag{4}$$

In this study, two statistical analyses were conducted using XLSTAT 2023. To statistically compare sediment grain-size characteristics between Kapota Atoll and Kapota Island, the mean grain size, sorting, skewness, and kurtosis values obtained using the Folk and Ward method were compared using the Mann–Whitney U test. This non-parametric test was selected because each location consisted of seven sampling stations ($n = 7$), resulting in a small sample size. The test was conducted using a two-tailed approach at a significance level of $\alpha = 0.05$, with the null hypothesis that there was no significant difference in the distribution of each grain-size statistical parameter between Kapota Atoll and Kapota Island. In addition, agglomerative hierarchical cluster analysis (AHC) was conducted to identify groups of sampling stations with similar sediment grain-size characteristics. The analysis was conducted using the Pearson correlation coefficient as the similarity measure and the weighted pair-group average method as the agglomeration method. Before clustering, the variables were centered and reduced (standardized) to minimize the influence of differences in scale among the sediment grain-size parameters. The number of clusters was determined based on the adapted Hartigan index, which was used to identify the most appropriate truncation level of the hierarchical clustering solution. The resulting dendrogram was then examined to identify groups of sampling stations exhibiting similar grain-size characteristics. Because the AHC was used as an exploratory classification approach, the resulting clusters were interpreted as groups of stations with similar sediment characteristics rather than as statistically validated populations, and no independent inferential test was applied to validate differences among the clusters. The cluster analysis was therefore used to characterize similarities among sampling stations rather than as an inferential test of differences between Kapota Atoll and Kapota Island.

3. Results and Discussion

3.1. Results Sediment Characteristics and Texture

The results of the granulometric analysis show that each sampling station has different sediment fraction compositions (**Table 2**). Only sediment samples from stations A6 and A7 lack sediment fractions <0.044 mm. These two stations are located in the northern part of Kapota Atoll, where the seabed is predominantly characterized by coral reefs, coral rubble, and sandy substrates with only limited seagrass cover (Hamuna et al., 2023). Such bottom conditions may favor the retention of coarser sediment fractions because the limited accumulation of very fine particles can be associated with local resuspension and sediment redistribution by waves and currents; however, these hydrodynamic processes were not directly measured in this study. Consequently, mud-sized sediments were absent at these stations, whereas coarser sediment fractions were retained on the seabed (Liang et al., 2020; Wang et al., 2023). Sediment particles ranging from 0.074 to 2.0 mm constituted the largest proportion of sediments at all sampling stations. However, the dominant grain-size class varied among locations. The 0.5–2.0 mm fraction predominated at all stations in Kapota Atoll and at stations P4 and P5 on Kapota Island, whereas the 0.25–0.5 mm fraction was dominant at stations P1 and P6, and the 0.074–0.25 mm fraction predominated at stations P2, P3, and P7. This spatial variation is closely related to differences in benthic habitat composition and hydrodynamic conditions. Stations dominated by coral reef and coral rubble substrates generally contained coarser grain sizes because coral pieces and shell debris are key sources of coarse carbonate sediments. Conversely, the stations associated with seagrass meadows and sandy bottoms (e.g., A2, A3, P2, and P3) tended to have a finer sand fraction because seagrass vegetation reduces near-bottom water movement, thus promoting the deposition and retention of finer sediments.

Table 2. Percentage weight of sediment grain-size fractions derived from dry sieving analysis and sediment texture classification at each sampling station based on the Gradistat analysis. Sand fractions ranging from 0.074–2.0 mm was dominant at most stations, while the main sediment textures identified were sandy gravel, gravelly sand, and slightly gravelly sand.

Stations	Percentage weight of fractions (%)							Sediment Texture (Gradistat)
	≥4.0 mm	2.0–4.0 mm	0.5–2.0 mm	0.25–0.5 mm	0.074–0.25 mm	0.044–0.075 mm	<0.044 mm	
A1	27.409	4.731	36.942	19.007	11.724	0.151	0.035	Sandy gravel
A2	7.197	12.029	33.925	12.198	32.303	1.419	0.929	Gravelly sand
A3	0.276	1.978	39.624	23.492	33.382	0.892	0.357	Slightly gravelly sand
A4	0.379	2.614	48.515	16.030	27.966	3.099	1.396	Slightly gravelly sand
A5	0.819	9.632	54.552	20.193	13.037	1.420	0.346	Slightly gravelly muddy sand
A6	3.681	16.943	60.115	17.042	2.202	0.016	–	Gravelly sand
A7	3.755	15.808	66.450	12.467	1.505	0.014	–	Gravelly sand
P1	25.595	5.094	14.064	30.094	25.083	0.055	0.014	Sandy gravel
P2	4.178	3.121	25.666	28.917	35.826	2.146	0.146	Gravelly sand
P3	4.178	5.017	27.204	18.563	40.972	2.674	1.393	Gravelly sand
P4	26.315	5.388	31.887	16.223	20.072	0.080	0.036	Sandy gravel
P5	36.346	8.206	40.119	6.041	8.747	0.361	0.180	Sandy gravel
P6	0.358	1.075	33.423	49.194	15.591	0.269	0.090	Slightly gravelly sand
P7	4.856	3.710	29.623	20.194	40.317	1.158	0.142	Gravelly sand

Overall, the Gradistat analysis indicated that sediments at both study sites consisted of three major fractions: gravel, sand, and silt (**Figure 3**). Sand was the dominant fraction at all stations (54.91–98.21%), followed by gravel (1.20–44.55%) and a minor proportion of mud (0.01–10.50%). Gravel was most abundant at stations A1, P1, P4, and P5, where coral fragments and shell debris were commonly observed, whereas mud occurred mainly at stations characterized by seagrass habitats and relatively sheltered bottom environments, consisting of very coarse mud and medium-coarse mud.

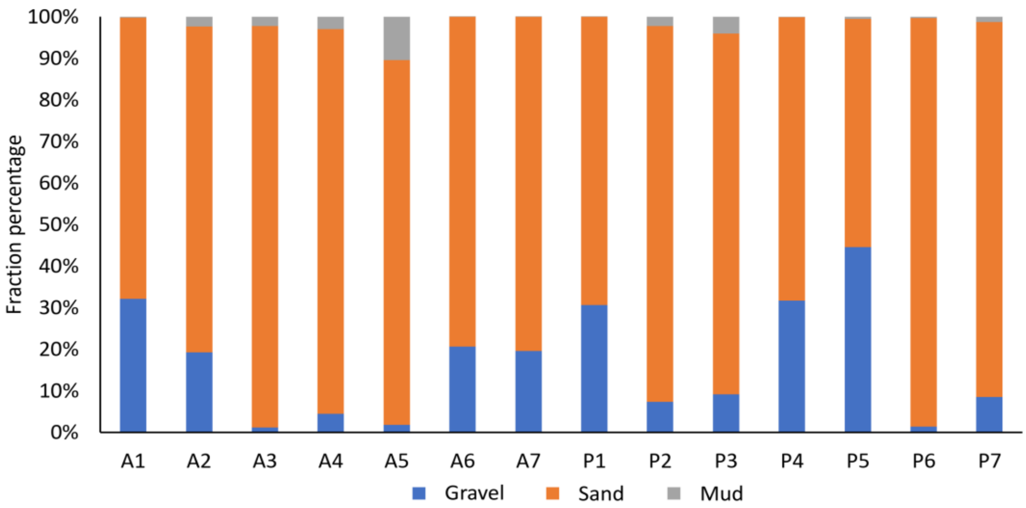

Figure 3. Percentage composition of gravel, sand, and mud fractions at each sediment sampling station based on the Gradistat analysis results. Sand was the dominant sediment fraction at all stations, whereas gravel and mud fractions showed relatively lower percentages. The spatial variation in fine-sediment content indicates differences in sediment characteristics among sampling stations.

Based on the analysis results from the Gradistat software, four types of sediment texture were identified: sandy gravel, gravelly sand, slightly gravelly sand, and slightly gravelly muddy sand (**Table 2**). Sediment texture at Kapota Atoll varied spatially among the sampling stations. Station A1, located on the outer reef, was characterized by sandy gravel associated with coral reefs and abundant coral rubble, whereas station A2 exhibited gravelly sand. Stations A3 and A4 were dominated by slightly gravelly sand, while station A5, located in the inner atoll, contained slightly gravelly muddy sand with abundant seagrass. In contrast, stations A6 and A7, located in the northern part of the atoll, were characterized by gravelly sand. These results indicate that sediment texture at Kapota Atoll is spatially heterogeneous rather than following a simple linear gradient from the outer reef toward the inner atoll.

The observed sediment texture pattern reflects the combined influence of geomorphological setting, benthic habitat composition, sediment source, and local hydrodynamic conditions. Kapota Atoll is an isolated reef system in which the outer reef is directly exposed to stronger wave and current energy, while the inner lagoon provides a relatively sheltered environment (Hamuna et al., 2023). Consequently, coarse carbonate sediments derived from coral fragmentation are preferentially retained in the outer reef, whereas finer sediment particles are transported and deposited within the inner atoll. Fine sediments generally accumulate in areas protected from strong wave action, whereas coarse sediments dominate areas subjected to higher wave energy and stronger currents (Wang et al., 2023). Variations in tidal currents and wave processes further influence sediment sorting and grain-size distribution (Venkatramanan et al., 2011; Nugroho and Basit, 2014; Bayhaqi and Dungga, 2015; Kurnio et al., 2018; Ma'arif and Hidayah, 2020; Liang et al., 2020). In addition to having weak currents on the inner side of the atoll, seagrass vegetation also plays an important role in the sediment particle deposition process, where seagrass vegetation can attach small to very small particles and deposit them around the seagrass vegetation (Stankovic et al., 2019; Leonardi, 2026).

Local differences in sediment properties between individual sampling sites suggest that habitat heterogeneity also exerts an important control on sediment distribution. The carbonate sediments at Kapota Island, stations P6 and P7, dominated by reefs of coral, coral Rubble, and sandy substrates, are abundant and have coarser sediment textures than stations P2, P3, and P4, where seagrass meadows and sandy bottoms are more common (Siregar et al., 2020). Likewise, stations A1, A2, A6 and A7 inside Kapota Atoll are mostly defined by reefs of coral and coral rubble, whereas stations A3, A4 and particularly A5 are progressively characterized by sandy bottoms and seagrass habitats (Hamuna et al., 2023). Changes in benthic habitat composition affect local hydrodynamics and sediment sources that may account for the geographical variability in sediment grain size and texture among collection stations.

Unlike Kapota Atoll, the sediment texture distribution around Kapota Island does not exhibit a clear spatial pattern. Near the coastline, station P4 is characterized by sandy gravel, while stations P2 and P3 in the central part are classified as gravelly sand. Station P5 also contains sandy gravel, whereas the outer stations exhibit different sediment textures, including slightly gravelly sand at station P6, gravelly sand at station P7, and sandy gravel at station P1. These variations primarily reflect differences in the local distribution of coral reefs, coral rubble, sandy bottoms, and seagrass habitats rather than a consistent geomorphological gradient (Siregar et al., 2020). Consequently, sediment sources and local hydrodynamic conditions vary over relatively short distances, producing heterogeneous sediment textures across Kapota Island. Nevertheless, the sediment textures identified in both Kapota Island and Kapota Atoll remain consistent with those reported for tropical coastal and shallow-water environments, where sand is generally the dominant sediment fraction (Purnawan et al., 2018; Kurnio et al., 2018; Setiawan et al., 2019; Nuraini and Wiyanto, 2021; Muhardi et al., 2021; Rachman et al., 2023). In general, finer sediment fractions tend to occur in deeper or more sheltered environments where mud, sandy mud, muddy sand, and very fine sand accumulate (Nugroho and Basit, 2014; Mulyadi et al., 2015; Putra and Nugroho, 2017; Kurnio et al., 2018).

3.2. Sediment Grain-Size Statistical Parameters

The results of the statistical analysis of sediment grain size parameters referring to Folk and Ward (1957) are presented in **Figure 4**. Mean grain size describes the central tendency of the grain-size distribution and provides a general characterization of the sediment deposited at each sampling station. Although mean grain size can be related to depositional conditions, it should not be considered a direct measure of water-flow or wave energy. The mean grain size in this study ranges from -0.118 to 3.182, which means that the sediment samples range from very coarse sand to very fine sand. Overall, very coarse sand is found only at station P5 and very fine sand only at station A5, while other stations have fine sand, medium sand, and coarse sand. The Mann–Whitney U test showed no significant difference in mean grain size between Kapota Atoll and Kapota Island (U = 26.0, p = 0.902) (**Table 3**), indicating that the overall distributions of mean grain size were statistically comparable between the two locations. At Kapota Atoll, sediment texture varied among sampling stations and did not follow a simple linear coarse-to-fine gradient from the outer to the inner part of the atoll. Coarser sediment occurred at stations A1, A6, and A7, including gravelly sand at A6 and A7, whereas finer sediment was observed at station A5. This spatial variation may reflect differences in depositional conditions, sediment sources, and the contribution of biogenic carbonate materials, such as coral and shell fragments, as well as differences in benthic habitat and reef morphology (Madden et al., 2013). Therefore, the spatial pattern observed at Kapota Atoll is better interpreted as spatial heterogeneity in sediment characteristics rather than direct evidence of a systematic gradient in current or wave energy.

Sorting shows the uniformity of grain size from a sediment sample (Folk and Ward, 1957) or can also be interpreted as the distribution of grain size relative to the mean grain size (Friedman, 1979). In this study, the sorting values range from 0.775 to 2.372, which indicates that the sediments are moderately sorted to very poorly sorted. Higher sorting values can indicate a less effective sorting process. The Mann–Whitney U test indicated no significant difference in sorting between Kapota Atoll and Kapota Island (U = 15.0, p = 0.259). The grain-size frequency distributions exhibited bimodal, trimodal, and polymodal patterns (**Figure 5**), reflecting differences in the number of dominant grain-size populations among the sediment samples. Stations A6 and A7 exhibited bimodal grain-size distributions, stations A2, A3, A4, P2, P3, P5, and P7 showed trimodal distributions, whereas stations A1, A5, P1, P4, and P6 displayed polymodal distributions. These modal characteristics are consistent with the observed sorting values, where poorly sorted sediments are generally associated with bimodal and trimodal distributions, whereas very poorly sorted sediments are predominantly associated with polymodal distributions. According to Hidayati (2017), poorly sorted sediments indicate a wide distribution of grain sizes and a greater degree of grain-size heterogeneity, whereas well-sorted sediments exhibit a narrower grain-size distribution.

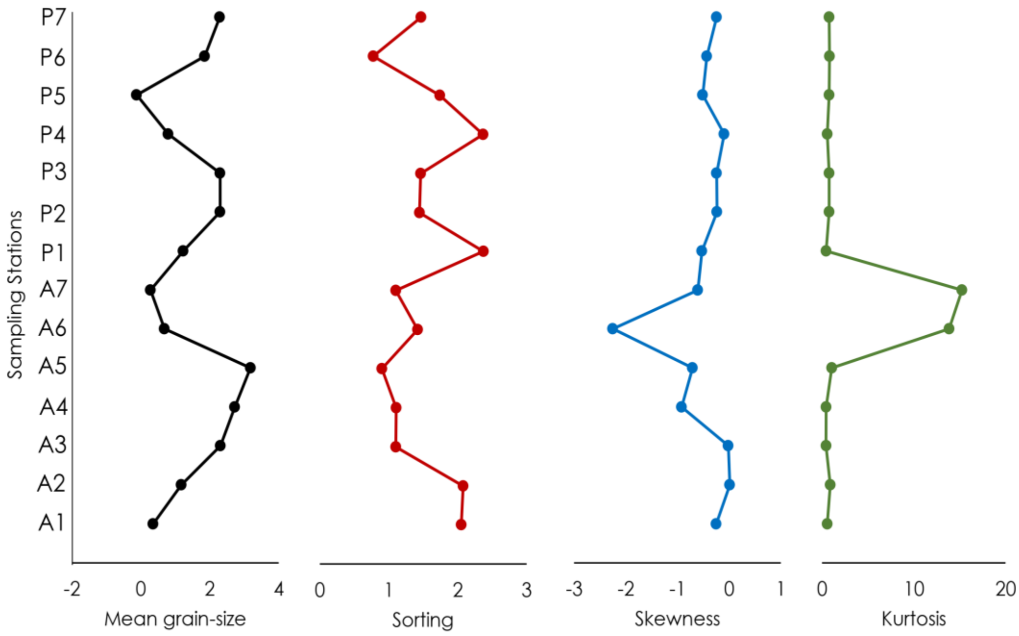

Figure 4. Statistical parameters of sediment grain size at each sampling station based on the Folk and Ward method (Folk and Ward, 1957), including mean grain size, sorting, skewness, and kurtosis. The figure shows that sediment characteristics varied from very coarse sand to very fine sand, with sorting values ranging from moderately sorted to very poorly sorted. The results further indicate that most sediment samples were negatively skewed and had predominantly platykurtic kurtosis values. The variation in mean grain size reflects differences in sediment characteristics and depositional conditions among stations, but does not directly represent hydrodynamic energy.

Table 3. Mann–Whitney U test comparing sediment grain-size statistical parameters between Kapota Atoll and Kapota Island.

Parameters	Kapota Atoll (Median)	Kapota Island (Median)	U	p-value
Mean grain size	1.176	1.859	26.0	0.902
Sorting	1.111	1.468	15.0	0.259
Skewness	−0.602	−0.243	17.0	0.383
Kurtosis	0.885	0.783	30.0	0.535

When more coarse sediment particles are present, the skewness will be negative, and vice versa. According to Folk and Ward (1957), skewness is the degree to which the sediment grain-size distribution deviates from a normal distribution. Only station A2 exhibits a positive value (positively skewed), indicating a relatively greater contribution of fine-sized sediment, whereas the other stations have negative values (negatively skewed). The skewness values in this study range from -2.247 to 0.014. Overall, the sediment samples obtained exhibited symmetrical, coarse-skewed, and very coarse-skewed skewness characteristics. The Mann–Whitney U test showed no significant difference in skewness between Kapota Atoll and Kapota Island ($U = 17.0$, $p = 0.383$). The predominance of negative skewness indicates a relatively greater contribution of coarser sediment fractions to the grain-size distributions. Such distributions may reflect differences in sediment sources and depositional conditions, including the selective transport and redistribution of finer particles (Martins, 1965; Friedman, 1979). Hydro-oceanographic processes such as coastal currents, waves, and tides may contribute to the transport and redistribution of fine particles (Nugroho and Basit, 2014); however, these processes cannot be directly evaluated from skewness alone.

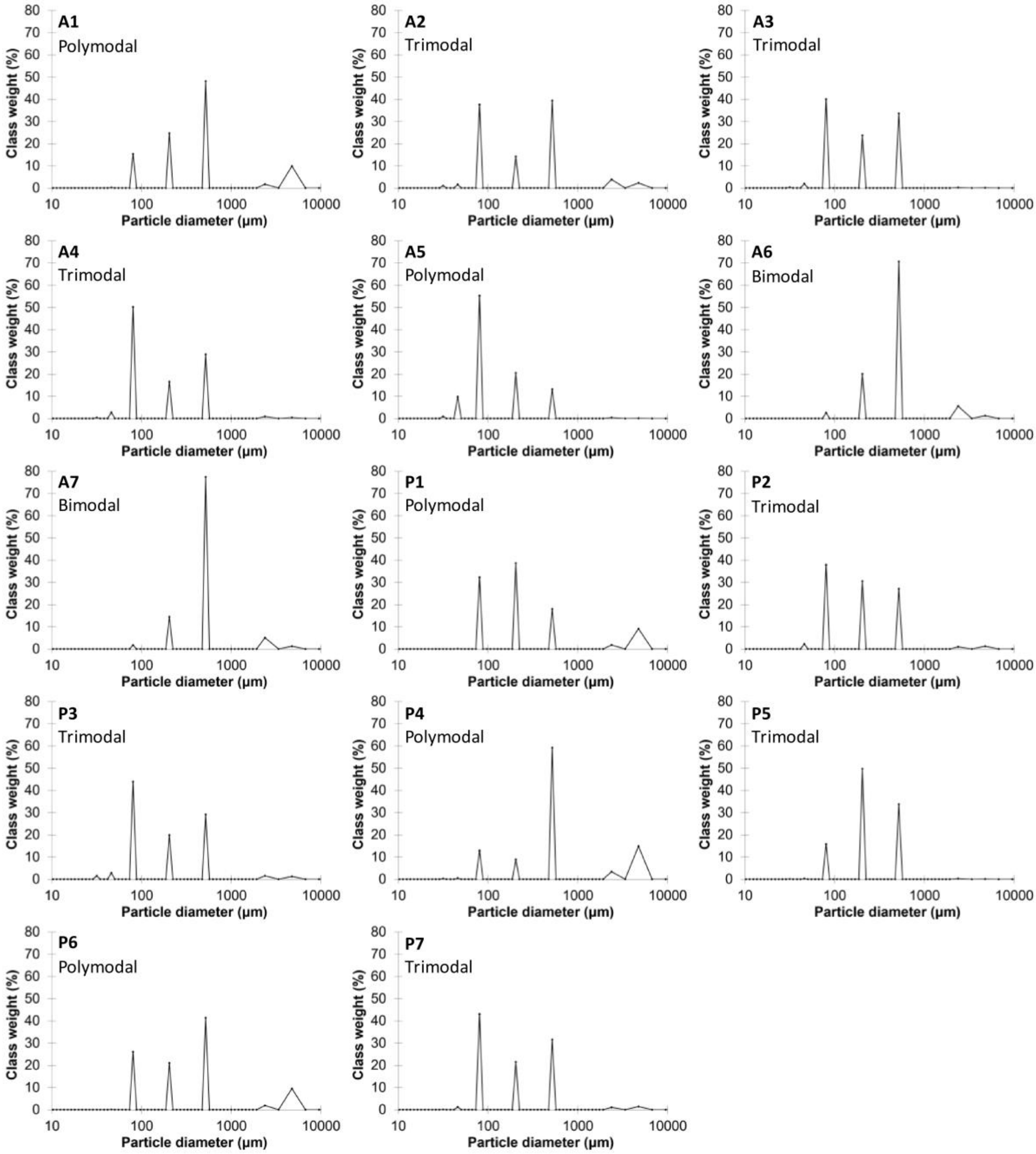

Figure 5. Grain-size frequency distribution curves of sediments at the fourteen sampling stations generated using Gradistat. The curves clearly show the number of dominant grain-size peaks in each sample, allowing the identification of bimodal, trimodal, and polymodal distributions that explain the observed differences in sediment sorting among the sampling stations.

Kurtosis can indicate the flatness of the sediment grain size distribution compared to a normal distribution (Folk and Ward, 1957). In this study, the kurtosis values obtained were predominantly low (0.433–1.055), except at stations A6 and A7, which had very high values (13.866 and 15.262, extremely leptokurtic). The high kurtosis values indicate that the frequency of sediment grain sizes is highly concentrated around the mean value (the distribution pattern is dominated by coarse sand and medium sand fractions). There are differences in kurtosis types between the location of Kapota Island and Kapota Atoll. In Kapota Island, only platykurtic and very platykurtic types are shown with a kurtosis curve that tends to be flat. Meanwhile, in Kapota Atoll, four types of kurtosis are found: very platykurtic, platykurtic, mesokurtic, and extremely leptokurtic, where the kurtosis values at stations A6 and A7 form a sharper curve compared to the other five stations. Despite the high kurtosis values observed at stations A6 and A7, the Mann–Whitney U test showed no significant difference in kurtosis between Kapota Atoll and Kapota Island (U = 30.0, p = 0.535). This result indicates a difference in kurtosis values between the stations in the southern and northern parts of the atoll. This condition is consistent with Rifardi's (2012) assertion that the shape of kurtosis's curve can be used to determine its characteristics; in other words, if the kurtosis value shows a sharp curve, it indicates that a specific size dominates the distribution of sediment grain sizes, and vice versa.

3.3. Sediment Sampling Station Grouping

The results of the sediment sampling station clustering based on cluster analysis are presented in **Figure 6**. The clustering was generated using Pearson correlation similarity and the weighted pair-group average agglomeration method after the variables were centered and reduced. The adapted Hartigan index indicated the appropriate truncation level for the four-cluster solution. The resulting clusters comprised stations with relatively similar grain-size fractions and statistical grain-size parameters, although stations within the same cluster were not necessarily located in the same geographical area. Four clusters of sampling stations were obtained, both based on the percentage of sediment grain size fractions (**Figure 6a**) and combined with the values of sediment grain size statistical parameters (**Figure 6b**). Cluster C1 consists of stations A1, P1, P4, and P5, which have similarities in the variables of sediment grain size ≥4 mm (gravel), sorting value, and skewness. Cluster C2 consists of stations A2, A4, and P3, with cluster-distinguishing variables including sediment grain size 0.074–0.25 mm (fine sand), 0.044–0.075 mm (silt), <0.044 mm (clay), mean grain size value, sorting, and skewness. Cluster C3 includes stations A3, P2, P6, and P7. The variables that distinguish this cluster are sediment grain size, specifically medium sand (0.25–0.5 mm), fine sand (0.074–0.25 mm), and silt (0.044–0.075 mm), along with the average grain size and skewness. The C4 cluster consists of stations A5, A6, and A7, with cluster-distinguishing variables including sediment grain sizes of 2–4 mm (gravel) and 0.5–2 mm (coarse sand) and kurtosis values (although there are significant differences between the kurtosis values of stations A6 and A7 compared to station A5).

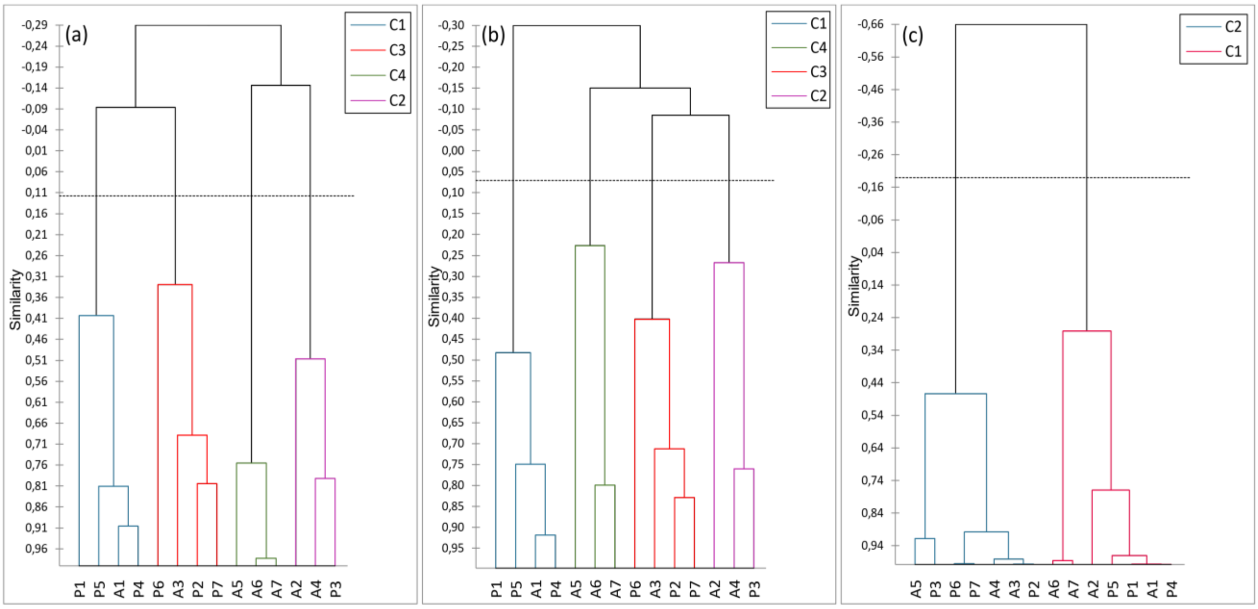

Figure 6. Cluster analysis of sediment sampling station groupings based on sediment grain-size characteristics and statistical parameters. The figure presents three clustering approaches: (a) percentage of sediment grain-size fractions, (b) combination of grain-size fractions and statistical parameter values, and (c) percentage of gravel, sand, and mud fractions. The clustering results demonstrate that most stations from Kapota Island and Kapota Atoll shared similar sediment characteristics, indicating relatively comparable sedimentation dynamics between the two study areas.

The simpler cluster analysis, which only looked at the percentage of gravel, sand, and mud, produced two clusters of sampling stations (**Figure 6c**). Cluster C1 consists of stations A1, A2, A6, A7, P1, P4, and P5, with the distinguishing parameter being the percentage of gravel fraction. Meanwhile, cluster C2, characterized by the percentage of sand and silt fractions, consists of stations A3, A4, A5, P2, P3, P6, and P7.

The clustering results indicate that the grouping of sampling stations reflects similarities in sediment characteristics rather than geographical location alone. Cluster analysis has been widely applied to identify sediment groups representing different depositional environments or lithofacies based on similarities in grain-size distributions and associated sedimentological parameters (Ordóñez et al., 2016; Devienna et al., 2022). In the present study, stations grouped within the same cluster exhibited comparable grain-size fractions and statistical grain-size parameters, indicating that they share similar sedimentary characteristics despite being located in different parts of Kapota Atoll and Kapota Island. These results suggest that the observed similarities in grain-size composition and statistical characteristics may reflect comparable depositional conditions, rather than being determined solely by the geographical separation between the two study areas.

Overall, the three clustering approaches consistently demonstrate that sediment grain-size characteristics are not strictly separated by geographical location. Most sampling stations from Kapota Atoll and Kapota Island were grouped together because they share similar sedimentological characteristics. Only stations A5, A6, and A7 formed a distinct cluster, indicating the presence of relatively unique sediment characteristics within the atoll environment.

4. Conclusions

The results of this study provide a comprehensive characterization of the sediment characteristics in Kapota Atoll and Kapota Island. The sediment consists of gravel fractions (fine gravel and very fine gravel), sand as the dominant fraction (coarse sand, medium sand, fine sand and very fine sand) and mud (very coarse mud and medium-coarse mud). Four sediment texture categories were identified at both study sites: sandy gravel, gravelly sand, slightly gravelly sand, and slightly gravelly muddy sand. Overall, sediment grain-size composition and statistical parameters indicate that the two study areas possess broadly similar sediment characteristics despite their different geomorphological settings. The Mann–Whitney U test showed no significant differences between the two locations in mean grain size, sorting, skewness, or kurtosis ($p > 0.05$). However, spatial heterogeneity in sediment texture was observed within both study areas. At Kapota Atoll, sediment grain-size characteristics varied spatially, with coarse and gravelly sediments occurring at stations A1, A6, and A7 and finer sediment occurring at station A5. This spatial variation suggests that sediment distribution across the atoll is heterogeneous rather than following a simple linear coarse-to-fine gradient from the outer reef toward the inner atoll. Furthermore, the kurtosis analysis suggests that Kapota Atoll sediments are more concentrated in a limited range of grain sizes compared to sediments around Kapota Island that are more spread out in a larger range of grain sizes. These results give significant baseline information for understanding the pattern of sediment deposition and enable future coastal environment management and environmental monitoring in Wakatobi National Park.

Conflicts of Interest

There are no conflicts to declare.

Acknowledgements

The authors would like to thank the Balai Taman Nasional Wakatobi for permitting this study.

AI Writing Statement

During the preparation of this manuscript, the authors used Chat GPT (OpenAI) for English translation and stylistic improvement. After using this service, the authors reviewed and edited the content as needed and takes full responsibility for the content of this publication.

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