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Analyzing sediment characteristics between intertidal and supratidal zones at Kelapa Kunjir Beach, Lampung Indonesia

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ABSTRACT

Kelapa Kunjir Beach, a coastal area vulnerable to sedimentation dynamics and abrasion threatening its stability and ecology, requires detailed sediment characterization. The differing tidal dynamic between its intertidal and supratidal zones significantly influence sediment distribution, yet a comparative analysis has been lacking. This study using quantitative description by comparatively analyzes sediment fractions, types, and granulometric parameters between these zones. Sediment samples from five stations per zone underwent dry sieving, granulometric statistical calculation (sorting, skewness, kurtosis), and classification via Shepard's triangle based on gravel, sand, silt, and clay proportions. Results show the intertidal zone is uniformly dominated by gravelly sand (gravel: 20.4%-35.5%, sand: 61.3%-78.7%; silt/clay absent). In contrast, the supratidal zone exhibits greater variability, featuring significant silt content (2.3%-39.2%) alongside gravel (16.4%-38.2%) and sand (41.3%-70.6%), classified as gravelly mud and muddy sand. Statistical analysis revealed moderately to poorly sorted sediments (sorting: 1.5–2.3), predominantly coarse-skewed (skewness: −0.8 to −0.07), and very leptokurtic (kurtosis: 1.7–4.0). It is concluded that distinct differences in grain size distribution and sediment types between the zones arise primarily from variations in environmental energy: the intertidal reflects moderate to high-energy conditions, while the supratidal indicates a lower-energy environment enabling fine material accumulation. These findings are crucial for guiding targeted coastal zone management and habitat restoration strategies.

Keywords: granulometric, sediment, intertidal zone, supratidal zone, Kelapa Kunjir Beach

PLAIN LANGUAGE SUMMARY

We studied sand types at Kelapa Kunjir Beach in Indonesia to understand how waves and tides affect coastal environments. We found two distinct areas: the zone covered by daily tides contains coarse sand because wave action washes away fine particles, while the upper beach area (flooded only during high tides) accumulates fine mud from land runoff. Human activities like tourism and fish farming increase the amount of fine sediment reaching the beach. Understanding these patterns helps coastal managers decide where to plant seagrass or mangroves to protect the shoreline and support marine life in tropical coastal areas.

Introduction

Coastal ecosystems are dynamic environments shaped by complex interactions between biotic (living organisms) and abiotic (physical-chemical) processes [1,2]. These interactions, particularly sedimentation patterns, critically determines shoreline resilience against erosion, coastal water quality, and the health of benthic (seafloor) habitats. Sediment characteristics—including type, grain size (granulometry), and stability—directly influence macrofaunal community structure, primary productivity (e.g., in seagrass beds), and nutrient cycling [3,4]. Ultimately, these processes underpin overall marine ecosystem productivity and form the foundation of livelihoods for coastal communities.

Kelapa Kunjir Beach, located in Sukajaya, Pesawaran Regency, Lampung, exemplifies a coastal system facing multiple anthropogenic and climatic pressures. Anthropogenic activities such as tourism, aquaculture (*tambak* ponds), and small-scale fisheries increase sediment input through soil erosion and increased turbidity. Additionally, global climate change drives sea-level rise and storm intensification, exacerbating tidal fluctuations and altering sedimentation dynamics. These combined pressures accelarate environmental degradation, diminishing ecosystem quality—including active seagrass meadows in the area [5].

The beach features complex geomorphology dominated by two distinct zones: intertidal zone and supratidal zone. The intertidal zone, regularly submerged by tides and wave action, experiences high-energy conditions that cause frequent changes in granulometry, mineral composition, and organic matter accumulation. Conversely, the supratidal zone, inundated only during extreme high tides, serves as a primary accumulation area for fine sediments transported during tidal cycles, potentially affecting long-term shoreline stability through altered sediment budgets [6].

Prior studies at Kelapa Kunjir noted sand and muddy-sand as dominant sediment types in seagrass ecosystems [7]. Research elsewhere (e.g., Pantai Biru, East Kalimantan) further established strong linkages among intertidal current velocity, nutrient levels (nitrate, phosphate), and sediment granulometry [6]. However, no comprehensive study has yet detailed and compared granulometric properties between Kelapa Kunjir's intertidal and supratidal zones—a critical knowledge gap given their divergent ecological functions and dynamics.

Addressing this gap carries both scientific and practical importance. Spatially resolved sediment dynamics at Kelapa Kunjir are essential not only for advancing fundamental understanding of tropical coastal sedimentation and habitat ecology but also for informing evidence-based management strategies. This research provides a robust scientific foundation for several key areas. First, it supports sustainable coastal planning by guiding the regulation of tourism, aquaculture, and fisheries to minimize environmental impacts. Second, it contributes to ecosystem conservation through the protection of vital seagrass meadows and benthic habitats. Third, it aids in erosion mitigation by informing the development of effective shoreline protection strategies in the face of climate-related threats. Thus, analyzing sediment characteristics across Kelapa Kunjir's intertidal to supratidal continuum represents a critical step toward enhancing coastal resilience, supporting local well-being, and informing broader tropical coastal management efforts.

Methods

Study location and time

The study was conducted at Kelapa Kunjir Beach, Sukajaya Lempasing, Padang Cermin, Pesawaran Regency, Lampung, on February 22, 2025.

Sampling design

Sediment sampling employed a purposive sampling approach across five stations positioned along a transect extending from areas of high to low anthropogenic influence. The first station was located nearest to anthropogenic activities (tourism, aquaculture, and fisheries), with subsequent stations placed at 100-meter intervals. At each station, samples were collected from both the intertidal and supratidal zones. Geographic coordinates for all sampling locations are detailed in Table 1 and visualized in Figure 1.

Collection and processing of sediment samples

Surface sediments (0-5 cm depth) were collected using a clean scoop, stored in labeled ziplock bags, and transported to the laboratory. One sample was collected from each station-zone combination (n=10 total). Samples were oven-dried at 110°C for 30 minutes prior to analysis.

Granulometric analysis was performed through dry sieving using a sieve shaker with graded mesh sizes 4.0, 2.0, 1.0, 0.5, 0.25, 0.125, and 0.063 mm for 10 minutes. Grain sizes were converted to phi (φ) scale using the formula [8]:

$$\varphi = -\log_2 \text{(grain diameter in mm)}$$

where higher phi values correspond to finer grain sizes. Weight percentages were calculated for each size fraction after drying. Grain size fractions were classified according to the Wentworth scale: gravel (>2 mm, <-1φ), sand (0.0625-2 mm, -1 to 4φ), silt (0.004-0.0625 mm, 4-8φ), and clay (<0.004 mm, >8φ). Sediment types were classified using Shepard's triangle diagram [9], based on the relative proportions of gravel, sand, silt, and clay.

Sediment statistical analysis

Statistical analysis of sediments provides fundamental insights into interpreting depositional dynamics in coastal environments. Parameters such as sorting (degree of grain selection), skewness (distribution asymmetry), and kurtosis (distribution peakedness) describe sediment segregation patterns and distribution formation influenced by hydrodynamic forces—waves, currents, and tides [9].

Granulometric parameters were calculated using KUMMOD Sel software following Folk and

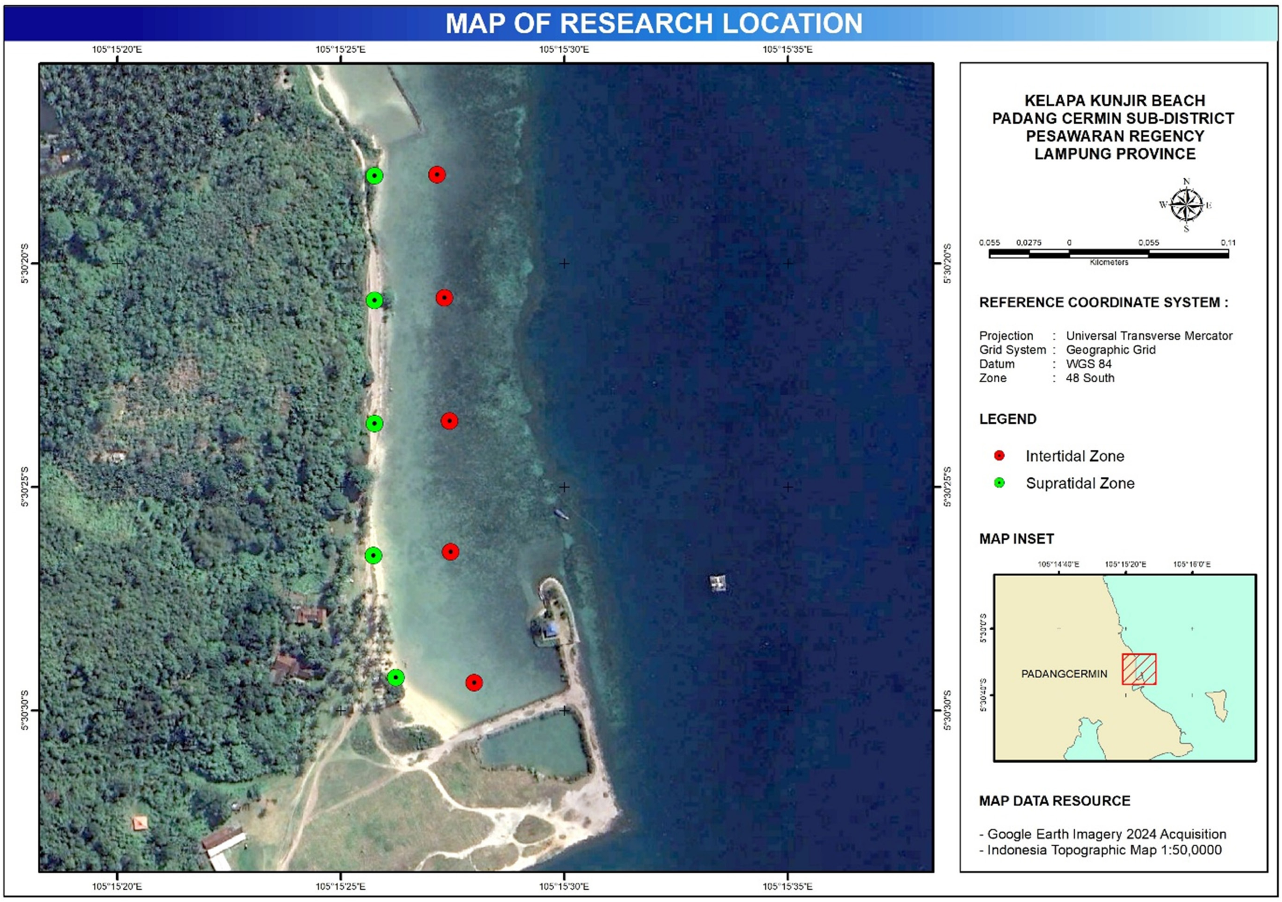

Figure 1. Study area map

Table 1. Geographic coordinates of sampling plots

Station	Coordinate	
	Intertidal zone	Supratidal zone
1	5°30'29.30"S, 105°15'28.00"EH	5°30'29.54"S, 105°15'26.50"E
2	5°30'26.63"S, 105°15'27.72"E	5°30'26.67"S, 105°15'25.77"E
3	5°30'23.12"S, 105°15'27.41"E	5°30'23.32"S, 105°15'25.80"E
4	5°30'20.99"S, 105°15'27.06"E	5°30'21.02"S, 105°15'25.77"E
5	5°30'17.91"S, 105°15'27.42"E	5°30'18.07"S, 105°15'25.82"E

Ward (1957) methods [10]. Four key statistical parameters were determined from cumulative grain size distribution curves:

Mean grain size (M):

$$M = \frac{Q_{16} + Q_{50} + Q_{84}}{3}$$

Sorting coefficient (S): measure of grain size uniformity

$$S = \frac{Q_{84} - Q_{16}}{4} + \frac{Q_{95} - Q_5}{6,6}$$

Skewness (Sk): Indicator of coarse/fine fraction dominance

$$Sk = \frac{Q_{84}+Q_{16} - 2Q_{50}}{2(Q_{84} - Q_{16})} + \frac{Q_{95} + Q_5 - 2Q_{50}}{2(Q_{95} - Q_5)}$$

Kurtosis (K): Measure of distribution peakedness

$$K = \frac{Q_{95} - Q_5}{2,44(Q_{75} - Q_{25})}$$

where Q_5, Q_{16}, Q_{25}, Q_{50}, Q_{75}, Q_{84}, and Q_{95} represent the 5th, 16th, 25th, 50th (median), 75th, 84th, and 95th percentile values of the cumulative grain size distribution, respectively.

Results

Sediment grain size distribution

Grain size distributions differed markedly between intertidal and supratidal zones (Figure 2A). In the intertidal zone, fine to very fine sand (2.0-3.0φ) was the dominant fraction at all stations, comprising 20.5-38.5% of total sediment weight (Figure 2B). Coarse material (gravel, -2.0 to -1.0φ) constituted 10-35% of intertidal sediments, with Station 1 showing the highest gravel content (33.3%) and Station 3 the lowest (14.1%). Silt-sized particles (4.0-5.0φ) were minimal, representing less than 8.5% at all intertidal stations.

The supratidal zone exhibited much greater variability in grain size distribution (Figure 2C). Fine to very fine sand (2.0-3.0φ) remained important (12.0-48.2%), but silt-sized particles (4.0-5.0φ) accumulated significantly, particularly at Station 3 (39.2%) and Station 1 (14.9%). Coarse fractions (-2.0 to -1.0φ) varied considerably between stations, ranging from 2.9% (Station 1) to 34.1% (Station 2). Station 5 showed intermediate silt accumulation (13.3%), while Stations 2 and 4 contained no detectable silt fractions.

Sediment statistical parameters

Statistical analysis revealed distinct characteristics between the two zones (Table 2). Sorting values indicated moderate sorting in the intertidal zone (1.5-1.9) and moderate to poor sorting in the supratidal zone (1.5-2.3). The supratidal zone showed greater variability, with Station 5 exhibiting the poorest sorting (2.3) and Station 1 the best sorting (1.5).

All samples displayed negative skewness values, confirming coarse-tail distributions. The intertidal zone showed skewness values ranging from -0.4 to -0.8, while the supratidal zone ranged from -0.07 to -0.8. Station 5 supratidal had the least negative skewness (-0.07), indicating a more symmetrical distribution.

Kurtosis values were consistently elevated (>1.7) across both zones, indicating peaked grain size distributions. The highest kurtosis value (4.0) occurred at supratidal Station 1, while the lowest values (1.7) were observed at intertidal Stations 1 and 2, and supratidal Station 4.

Sediment composition and types

Sediment type analysis in intertidal and supratidal zones is critical for understanding deposition processes and sediment distribution that shape coastal ecosystem structures. Sediment types strongly correlate with benthic community diversity and distribution. In intertidal zones, for instance, sediment type alterations can modify benthic community structures that depend heavily on substrate size and consistency [12,13].

Sediment classification analysis revealed uniform characteristics in the intertidal zone versus high variability in the supratidal zone. The intertidal zone was consistently classified as “gravelly sand” across all five stations (Figure 3 left side). Gravel content ranged from 20.4% (Station 3) to 35.5% (Station 2), while sand content varied from 61.3% (Station 5) to 78.7% (Station 3). Silt fractions were minimal, reaching a maximum of 8.5% at Station 5, with most stations showing no detectable silt content.

The supratidal zone exhibited four different sediment classifications (Figure 3 right side). Stations 1 and 2 were classified as “gravelly sand,” similar to the intertidal zone. However, Station 3 was classified as “slightly gravelly mud” due to its high

Table 2. Statistical parameters in intertidal and supratidal zones

	Intertidal zone			Supratidal zone		
	Sorting	**Skewness**	**Kurtosis**	**Sorting**	**Skewness**	**Kurtosis**
Station 1	1.9	-0.4	1.7	1.5	-0.3	4
Station 2	1.5	-0.5	1.7	2.1	-0.7	1.8
Station 3	1.7	-0.8	2.6	1.8	-0.8	3
Station 4	1.7	-0.7	2.5	1.9	-0.4	1.7
Station 5	1.5	-0.8	2.5	2.3	-0.07	2.3

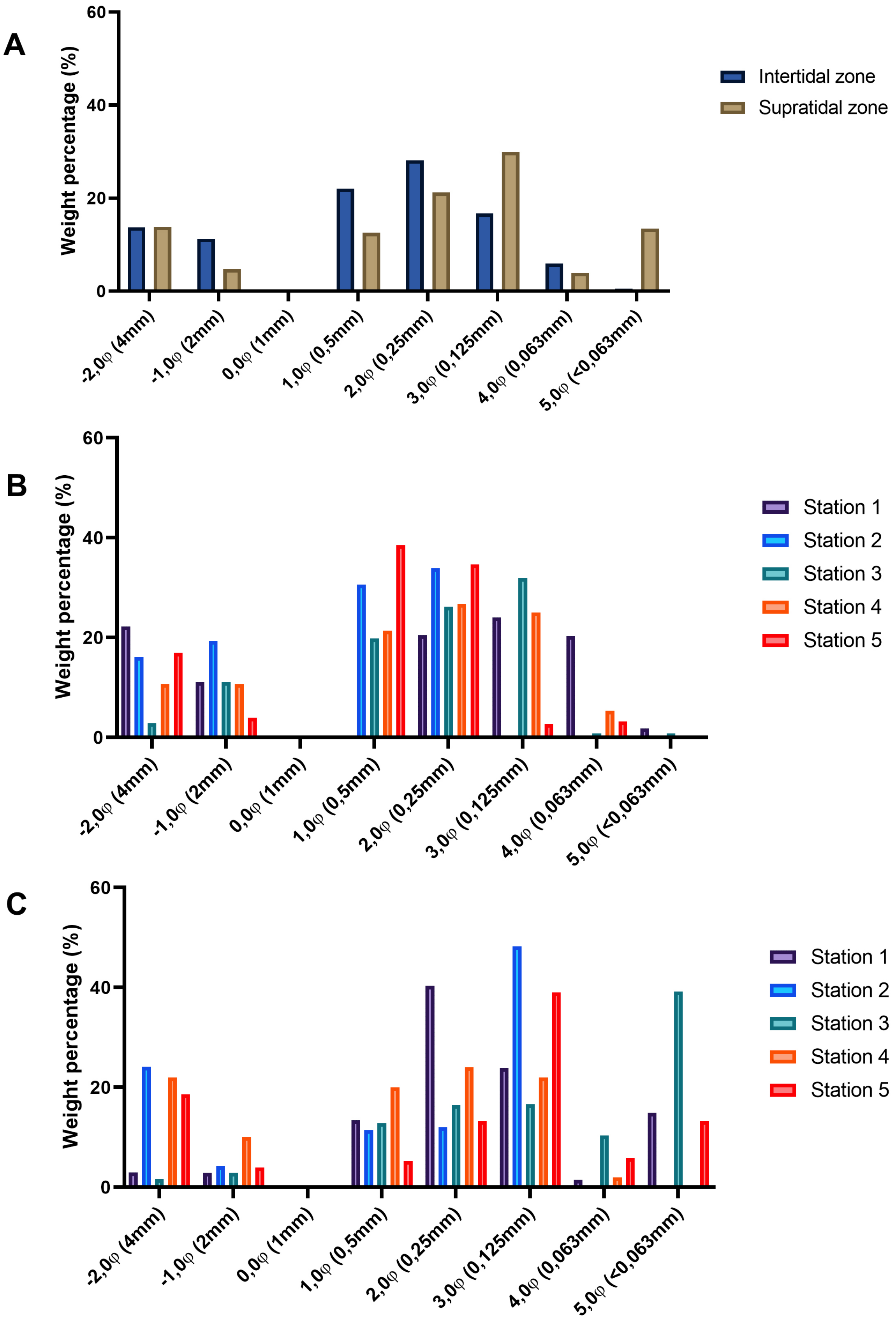

Figure 2. Grain size distribution patterns across intertidal and supratidal zones at Kelapa Kunjir Beach. (A) Average grain size distribution comparing intertidal (dark blue) and supratidal (brown) zones. **(B)** Individual intertidal station distributions showing consistent sand-dominated patterns. **(C)** Individual supratidal station distributions demonstrating high spatial variability, with notable fine sediment accumulation (39.2% at 5.0φ) at Station 3. Grain sizes in phi (φ) scale: -2.0φ = 4 mm (gravel), -1.0φ = 2 mm (gravel), 0.0φ = 1 mm (coarse sand), 1.0φ = 0.5 mm (medium sand), 2.0φ = 0.25 mm (fine sand), 3.0φ = 0.125 mm (very fine sand), 4.0φ = 0.063 mm (silt), 5.0φ = <0.063 mm (fine silt)

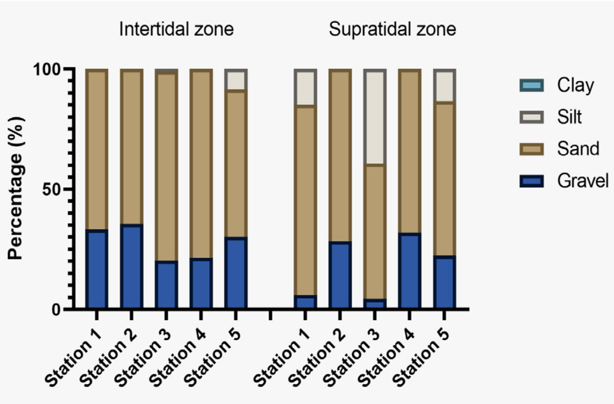

Figure 3. Percentage of sediment fractions and sediment types in the intertidal zone (left) and supratidal zone (right)

silt content (39.2%), Station 4 as "sandy gravel" with 32% gravel content, and Station 5 as "gravelly muddy sand" containing 13.3% silt. Clay fractions were absent in all samples from both zones.

Discussion

The intertidal and supratidal zones exhibit distinct environmental characteristics primarily governed by tidal regimes and wave energy gradients. These differential energy conditions critically influence sediment deposition patterns, which are further modulated by hydrodynamic forces, local topography, and anthropogenic activities [14]. The intertidal zone experiences regular tidal inundation and higher energy fluctuations compared to the supratidal zone, resulting in characteristic sediment distributions essential for understanding coastal morphodynamics, benthic habitat structuring, and ecosystem resilience.

The grain size patterns reflect distinct hydrodynamic energy regimes operating across the beach profile. The dominance of fine to very fine sand (2.0-3.0φ) in the intertidal zone indicates moderate to high-energy conditions where wave action selectively transports fine particles seaward while retaining coarser material [14]. This selective sorting process creates the characteristic coarse-tail distributions observed in wave-dominated environments. The substantial coarse fractions (10-35% gravel) further confirm the winnowing action of waves and tidal currents that remove fine particles during each tidal cycle [15].

The supratidal zone shows markedly different depositional patterns, with significant fine sediment accumulation reflecting lower-energy conditions. The progressive landward attenuation of wave energy allows silt and clay particles from terrestrial runoff to settle and accumulate [12,16]. The extreme silt accumulation (up to 39.2%) at certain locations demonstrates the effectiveness of supratidal areas as sediment traps during infrequent high-tide inundation events. These fine sediments support biofilm development and microbial communities that drive coastal biogeochemical cycling [12].

The statistical parameters provide additional insight into depositional processes operating in each zone. Moderate sorting in the intertidal zone (1.5-1.9) reflects consistent wave winnowing that selectively removes specific grain size fractions, while poorer sorting in the supratidal zone (1.5-2.3) indicates more variable depositional conditions where multiple transport mechanisms contribute sediment [16,17]. The slightly better sorting at some intertidal stations suggests more effective hydraulic sorting under regular wave action.

Consistently negative skewness values across both zones (intertidal: -0.4 to -0.8; supratidal: -0.07 to -0.8) confirm coarse-tail distributions typical of beach environments where wave action preferentially removes fine particles [18]. The less negative skewness in some supratidal samples reflects the retention of fine fractions under low-energy conditions. High kurtosis values (>1.7), particularly the peak value of 4.0 in supratidal areas, suggest episodic deposition events that concentrate specific grain size ranges, possibly related to storm-driven transport or seasonal variations [19].

Sediment composition differences between zones create distinct ecological niches that support different biological communities. The uniform gravelly sand classification in the intertidal zone (gravel: 20.4-35.5%; sand: 61.3-78.7%) provides stable, well-drained substrate conditions where fine particles are consistently winnowed during tidal cycles. This coarse substrate supports diverse macrozoobenthic communities (polychaetes, amphipods, bivalves) adapted to dynamic, high-energy conditions [15]. The coarse texture facilitates oxygen penetration and drainage during tidal exposure, creating favorable conditions for aerobic decomposition.

The supratidal zone exhibits marked heterogeneity, with silt content reaching 39.2% at some locations.

This fine sediment accumulation results from low-energy conditions and terrestrial runoff [20], creating microhabitats that support different biological processes. Fine sediments retain moisture and organic matter more effectively, promoting microbial activity and serving as nutrient reservoirs. These conditions foster biogeochemical processes including mineralization and denitrification—critical for water quality stability and blue carbon sequestration [13,21]. However, excessive fine sediment accumulation may also lead to anoxic conditions that stress benthic communities.

The statistical parameters recorded fall within ranges reported for comparable tropical beach systems. The predominantly negative skewness values match patterns observed in wave-dominated tropical beaches where consistent wave action creates characteristic coarse-tail distributions [17]. However, our study reveals greater spatial variability in supratidal characteristics than typically reported, possibly reflecting local anthropogenic influences on sediment supply and transport patterns. The extreme silt accumulation (39.2%) observed at Station 3 supratidal exceeds values commonly reported for natural beach systems, suggesting enhanced terrestrial input from nearby anthropogenic activities.

These findings provide evidence-based guidance for coastal management strategies at Kelapa Kunjir Beach. The stable, coarse-textured sediments in the intertidal zone make this area particularly suitable for seagrass restoration efforts, as these conditions provide the substrate stability, adequate drainage, and light penetration that seagrass communities require [6]. Conservation efforts should focus on maintaining natural sediment transport processes that sustain these favorable conditions through appropriate regulation of coastal activities.

The supratidal zone's role as a fine sediment repository requires different management approaches. While some fine sediment input is natural and supports important biogeochemical functions, excessive accumulation from anthropogenic sources should be controlled to prevent habitat degradation and anoxic conditions. Management strategies should include controlling terrestrial runoff from aquaculture and tourism activities, particularly during monsoon periods when sediment transport is maximized [4]. Buffer zones around aquaculture facilities and improved drainage management could help reduce excessive fine sediment delivery to supratidal areas.

Integrating sediment characteristics into coastal zoning ensures that restoration efforts align with natural hydrodynamic processes, maximizing the success of conservation initiatives while maintaining ecosystem services. The contrasting sediment environments suggest that different management strategies should be applied to each zone rather than uniform approaches across the entire beach system.

Several limitations should be considered when interpreting these results. Our single sampling event in February 2025 provides only a snapshot of sediment characteristics and cannot capture seasonal variations related to monsoon cycles, storm events, or biological activity. The spatial scale of our study (five stations over 400 meters) may not capture broader alongshore variations or represent conditions at other times of year when sediment transport patterns may differ significantly.

The lack of temporal data limits our ability to assess whether the observed patterns represent stable conditions or temporary fluctuations. Seasonal variations in precipitation, wave energy, and anthropogenic activities may substantially alter sediment transport and deposition patterns. Additionally, our sampling approach focused on surface sediments (0-5 cm depth) and may not capture subsurface processes or longer-term depositional history.

Future research should include seasonal sampling to quantify temporal variations in sediment characteristics and identify the relative importance of natural versus anthropogenic factors in controlling sediment distribution. Long-term monitoring would help detect trends related to climate change, sea level rise, and evolving development pressures. Priority research directions include: (1) quantification of sediment transport rates using direct measurement techniques, (2) assessment of seasonal and storm-driven variations in sediment patterns, (3) detailed analysis of sediment sources using geochemical tracers, and (4) evaluation of the relationship between sediment characteristics and biological community structure.

Expanding the study to include additional beaches in the region would enhance understanding of regional sediment dynamics and improve the generalizability of findings for tropical coastal management. Integration with hydrodynamic modeling could also help predict future changes in sediment distribution under different climate and development scenarios.

Conclusion

This study demonstrates distinct sediment characteristics between the intertidal and supratidal zones at Kelapa Kunjir Beach, shaped by contrasting environmental energy regimes and anthropogenic influences. The intertidal zone is dominated by homogeneous coarse sediments (gravelly sand) due to high wave energy that winnows fine particles, while the supratidal zone shows extreme variability (with silt accumulation up to 39.2%) driven by low-energy terrestrial runoff and human activities.

These patterns are supported by sediment statistics: moderate to poor sorting (1.5–2.3) reflects varying energy conditions, while high kurtosis (>1.7) and consistently negative skewness (-0.8 to -0.07) confirm coarse-particle dominance and hydraulic sorting processes. Anthropogenic pressures (e.g., aquaculture, tourism) enhance fine sediment input, exacerbating supratidal heterogeneity.

Ecologically, coarse intertidal sediments support diverse macrozoobenthic communities, whereas fine supratidal sediments serve as nutrient reservoirs that promote microbial activity. For effective management, we recommend zone-specific strategies: seagrass conservation in the intertidal zone to maintain substrate stability, and mangrove rehabilitation in the supratidal zone to optimize fine sediment processing and nutrient cycling.

This study focuses solely on the analysis of sediment distribution using statistical methods. It is recommended that future research include additional analyses, such as sediment classification based on the Shepard triangle, analysis of finer sediment fractions, and geomorphological characterization of sediment textures.

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Declaration of interest

None.

Author contributions

Conceptualization: DS; methodology: MAD; Project administration: DS; Software: DS; Resources: DS, MAD; Visualization: MAD; Writing – original draft: DS, MAD; Writing – review & editing: DS, MAD.

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