Malaysian Journal of Soil Science 2025 Vol. 29: 363-378

Sediment Analysis and Textural Characterization: A Case Study from the Kelantan and Terengganu Coasts, Peninsular Malaysia

Mohamad, Ahmad Ansar[1]; Rehman, Muhammad Ali[2]; Murtadza, Muzzammil[3]; Omar, Syed[3]; Abd Jalil, Amin Noorasid[3]; Shaarani, Noran Alwakhir[3]; Abd Rahim, Muhammad Anasrullah[3]; Mansor, Nur Muhammad Asyraf[3]; & Mohd Razip Wee, Mohd Farhanulhakim[4*]

[1]Atlas Geosurvey SDN. BHD. 53300, Kuala Lumpur (W.P)
[2]Department of Civil Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 UKM Bangi, Selangor, Malaysia
[3]Bahagian Perkhidmatan Teknikal, Jabatan Mineral Dan Geosains Malaysia, Jalan Sultan Azlan Shah, 31400 Ipoh, Perak, Malaysia
[4]Institute of Microengineering and Nanoelectronics, UKM, Bangi 43600, Selangor, Malaysia

**Correspondence: m.farhanulhakim@ukm.edu.my*

ABSTRACT

This study provides a comprehensive seabed sediment and textural analysis of surface sediments from the nearshore beach areas of Kelantan and Terengganu coasts along the South China Sea. Employing a set of laboratory analyses, including particle size distribution, X-ray fluorescence (XRF), and determinations of organic matter and carbonate content, we examined the variability in grain size, organic content, carbonate levels, and the concentrations of major elements and oxides. Findings indicate a dominance of very fine sand, accounting for 28% of the sediment composition, suggesting dynamic, moderate-energy depositional environments. Silicon emerged as the most prevalent element with a mean concentration of 39.46%, ranging from 14.10% to 45.90%, while Silicon Dioxide (SiO_2) was the dominant oxide, with a mean of 85.11% and a range from 30.10% to 98.20%. The study also reveals mean organic content at 0.83% and carbonate content at 15.39%, which together underscore the complex interplay between biogenic accumulation and mineralogical compositions in these coastal sediments. These insights not only advance the understanding of sediment dynamics in tropical coastal regions but also provide critical data for environmental management and conservation efforts, aiming to protect these ecologically sensitive and economically vital coastal zones.

Keywords: Coastal Sediments, Sediment Analysis, Sediment Composition, Grain Size Distribution, Elements and Oxides

INTRODUCTION

Coastal erosion, intensified storm activities, influx of pollutants from agricultural runoff, industrial discharge, and urbanization endanger the health of coastal ecosystems (Nunes & Leston, 2022). Coastal areas are generally shaped by a combination of terrestrial and marine processes, resulting in the deposition of sediments that are vital for maintaining the coastal ecosystems (Carr *et al*., 2003). These sediments, transported by rivers, tides, and ocean currents, not only influence the physical characteristics of the coastline but also serve as indicators of environmental health (Ouillon, 2018). The chemical composition of these sediments offers critical insights into various geological processes, sediment provenance, weathering, transportation, and deposition (Hernandez-Hinojosa *et al*., 2018; Ma *et al*., 2017; Wittkop *et al*., 2020) and also play a crucial role in reconstructing past climatic and environmental conditions (Liu *et al*., 2022; Skurzyński *et al*., 2020). The sediment and mineralogical compositions of surface sediments is influenced by various natural and anthropogenic factors including geology, weathering, erosion, hydraulic sorting and differentiation in grain size (Garzanti & Resentini, 2016; Guo *et al*., 2018; Lupker *et al*., 2012).

Approximately half of the world's coastlines are composed of sand and gravel, largely due to sediment transport and deposition from rivers and terrestrial sources (Bird, 2008). Sandy beaches are predominantly composed of quartz-feldspathic sand, usually comprising heavy minerals in abundance (Pupienis *et al*., 2017). The physical, textural, mineralogical, and elemental properties of these beaches are shaped by multiple factors. These include the geographic and environmental conditions of the region, the underlying geological framework, and tectonic influences that impact the formation of the landscape (Barnard *et al*., 2013; Jarmalavičius *et al*., 2017; Saha *et al*., 2010). Additionally, sediment provenance, climate, and the dynamics of the sea, such as tides, waves, and currents, play a significant role in determining beach characteristics (Karlonienė *et al*., 2021). The concentrations of major elements (such as silicon, aluminium, iron, magnesium, calcium, sodium, and potassium), trace metals (such as lead, zinc, copper, chromium, and nickel), and organic content are commonly analysed in sediment studies to determine the provenance, weathering intensity, and human impact on the sediments (Esen *et al*., 2010; Hossain *et al*., 2021; Yang *et al*., 2018; Zonneveld *et al*., 2010). The concentration of major and trace elements in marine sediments can fluctuate over time due to various factors such as direct human activities, riverine and wind-borne transport from land, marine currents, and atmospheric deposition (El Idrissi *et al*., 2024). Research conducted on trace elements in beach sediments worldwide typically associates the elevated levels of trace metals in coastal sediments with industrial discharge, urban runoff, and agricultural activities, making them reliable markers of anthropogenic pollution (Paul *et al*., 2024; Ra *et al*., 2013; Vetrimurugan *et al*., 2017). The presence of trace metals and heavy metals in coastal sediments might cause serious contamination of the marine environment (Yalcin *et al*., 2015). These contaminants in the surface sediments can remobilize into the marine system and subsequently bioaccumulate in marine organisms, leading to the degradation of water quality and marine habitats, loss of biodiversity, and food chain contamination, causing severe diseases (Kolarova & Napiórkowski, 2021; Ling *et al*., 2022). Therefore, a thorough and intricate understanding of beach dynamics is crucial, as alterations in beach morphology and quality can have significant economic and social consequences.

The northeastern coastal regions of Peninsular Malaysia, specifically Kelantan and Terengganu, are characterized by their extensive and dynamic coastlines, which play a crucial role in supporting the local economy through activities such as fishing, tourism, and small-scale agriculture. While sediment geochemistry has been extensively studied in various regions of Malaysia (Ahmad *et al*., 2012; Rezaee Ebrahim Saraee *et al*., 2011; Rezaee *et al*., 2011; Sany *et al*., 2011; Shaari *et al*., 2020; Yap & Pang, 2011), there is a noticeable lack of comprehensive studies focused on the beach sediments of the northeastern coasts of Kelantan and Terengganu. Given the unique geographical and environmental conditions of these regions, influenced by distinct monsoon patterns and riverine inputs, it is essential to investigate how these factors impact sediment composition. This study seeks to fill this gap by providing a detailed analysis of the surface sediments of beach areas in these coastal regions, contributing to the broader understanding of sediment dynamics in tropical environments.

The objective of this study is to conduct a comprehensive sediment constituent profiling analysis of surface sediments collected from the nearshore beach areas of the coasts of Kelantan and Terengganu, along the South China Sea. This analysis will focus on identifying and quantifying the concentrations of carbonate content, organic matter, and grain size distribution within the sediments. This study makes a significant contribution to the field of sediment geochemistry, particularly within the context of tropical coastal environments. By providing a detailed sediment and textural characterization of surface sediments in the Kelantan and Terengganu regions, this research addresses the gap in knowledge regarding sediment composition in these underexplored coastal areas. The findings enhance the understanding of how natural processes, such as riverine inputs and monsoonal rainfall, interact with anthropogenic activities to influence the geochemical makeup of coastal sediments.

MATERIALS AND METHODS

Study area

Malaysia is influenced by maritime and wind systems originating from both the Indian Ocean and the South China Sea. The country experiences two major monsoon seasons each year: the southwest monsoon (SWM) and the northeast monsoon (NEM). The SWM, which spans from May to September, primarily brings rainfall to the west coast of Peninsular Malaysia. In contrast, the NEM, occurring from November to March, typically results in heavy rainfall and frequent flooding, particularly affecting the eastern coastal states of Kelantan, Terengganu, and Pahang (Ariffin *et al*., 2018). The northeastern coast of Peninsular Malaysia stretches along the South China Sea and is known for its expansive sandy beaches and dynamic coastal systems. These coastal processes, along with riverine inputs from rivers such as the Kelantan and Terengganu Rivers, play a significant role in sediment transport and deposition along the shorelines. The marine sediments in the offshore areas of Kelantan and Terengganu coasts along the South China Sea typically consist of a mixture of sand, silt, clay, and mud (Shaari *et al*., 2015). These materials are transported by rivers and ocean currents, gradually accumulating in the region over time.

Sampling

The samples were collected along the coasts of Kelantan and Terengganu near the beach area, as depicted in **Figure 1**. For this study, a Van Veen grab sampler was utilized to collect sediment samples, which is suitable for collecting surface sediments from soft, fine-grained materials to moderately compact sandy substrates, though it may not be effective in hard-packed or cohesive clayey sediments (Beukema, 1974). The jaws of the sampler close under their weight, enclosing the sediment with minimal disturbance. To avoid sampling bias across large stations along the east coast of Peninsular Malaysia, three sediment samples were collected at each station by releasing the sampler three times, spaced approximately 1 meter apart. The collected samples were then transferred into pre-cleaned and pre-weighed polyethylene containers and stored at -5 °C to preserve the integrity of the sediment composition by preventing any elemental changes that might occur at room temperature. In total, 199 grab samples were collected during this phase for subsequent sediment constituent analysis.

Grain Size Distribution

In the laboratory, sediment samples from each designated site were subjected to detailed particle size analysis using both wet and dry sieving techniques (Cha *et al*., 2007). A 350g subsample of wet sediment was accurately weighed and soaked overnight in a 0.5% Calgon solution to facilitate particle dispersion. Wet sieving was then conducted using a 63-micron sieve, effectively separating the sample into sand and mud fractions. Both fractions were carefully dried on a hot plate, after which their weights were recorded, enabling the calculation of the total sample weight.

For the dry sieving process, the entire dried sand fraction was placed in a stack of 16 sieves, ranging in size from 2000 microns to pan level, and shaken for 20 minutes. Each fraction retained by the sieves was carefully collected, labelled with the corresponding micron size, and weighed. The recorded weights were subsequently entered into a computer for analysis, using pre-programmed calculations to generate a comprehensive particle size distribution profile for each sediment sample. This methodical approach ensures an in-depth understanding of the sediment's composition and grain size distribution, providing critical insights into the environmental conditions of the study area.

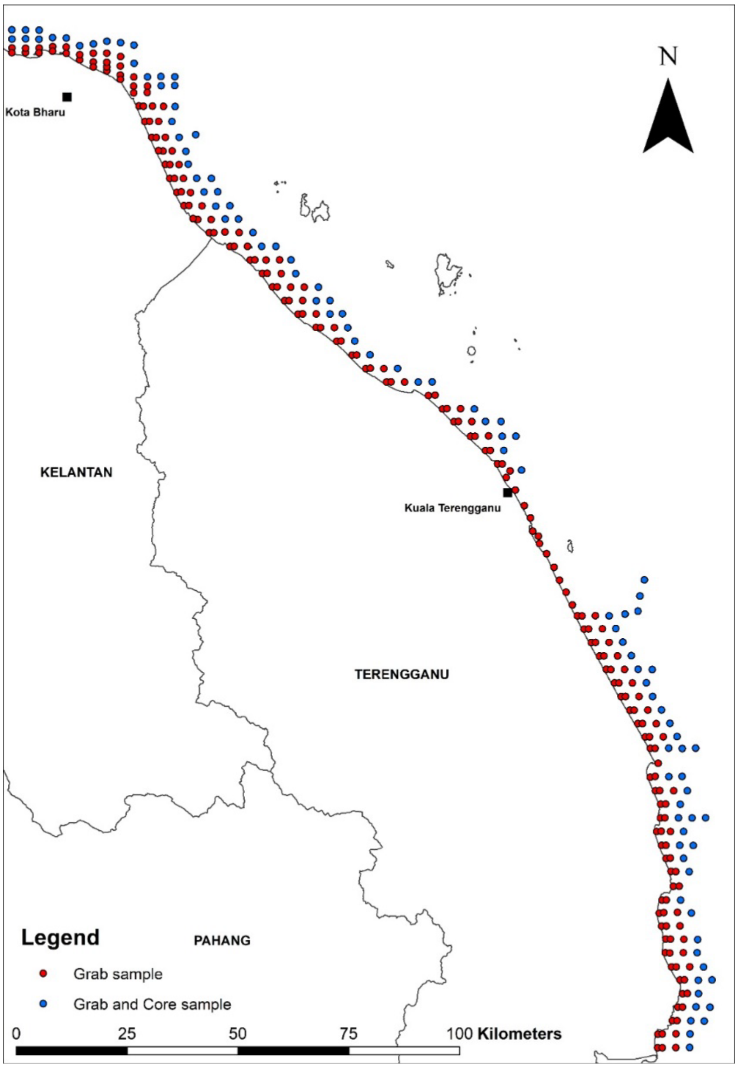

Figure 1. Sampling Point of Surface Sediments along the South China Sea

Organic content

The organic matter content of the sediment samples was determined using the oxidation method with hydrogen peroxide, following the procedure described by Heiri *et al*. (2001). The procedure follows a series of carefully controlled steps to ensure accuracy and consistency. Initially, 600ml beakers were labelled for identification and preheated to 30°C for 10 minutes, creating a controlled environment for subsequent steps. Meanwhile, the sediment samples were preheated at 60°C for 20 minutes to facilitate drying and improve the accuracy of measurements. After the preheating, the samples were cooled for 15 minutes to reach a suitable temperature for analysis. The empty, preheated beakers were then weighed using a precision balance to ensure accurate baseline measurements, critical for determining the organic content later in the process.

Next, a precisely weighed 20.00 g portion of the preheated sample was placed into a weighing pan and carefully transferred into the preheated beaker. The sample was moistened with distilled water, followed by the addition of 40 ml of hydrogen peroxide to initiate the chemical reaction required for organic analysis. The beakers were then left to stand overnight to allow the reaction to fully take place, ensuring an accurate determination of the organic content. After incubation, the samples were dried on a hot plate to remove any remaining moisture. They were then transferred to an oven preheated to 60°C and dried for an additional 30 minutes to finalize moisture removal. Once out of the oven, the samples were cooled for 20–25 minutes, after which the beakers were reweighed on the precision balance. The difference in weight before and after the drying process reflects the organic content of the sample. Careful record-keeping at each stage ensures the accuracy and reliability of the results.

Carbonate content

The carbonate content of the sediment samples was determined using the Gravimetric Acid Digestion Method, following the general procedure outlined by Loeppert and Suarez (1996). The procedure involves a structured series of steps to accurately measure the carbonate content of a sample. The process begins by labelling 600 ml beakers and preheating them to 30°C for 10 minutes to establish a controlled environment. Meanwhile, dried samples designated for analysis are preheated at 60°C for 20 minutes and then allowed to cool for 15 minutes. Once the preheating and cooling phases are completed, the empty beakers are weighed using a precision balance, as accurate measurements at this stage are critical for subsequent calculations. Afterward, 20 g of the preheated sample is carefully weighed and transferred into the preheated beaker.

To initiate the chemical reaction necessary for carbonate analysis, the sample is moistened with distilled water, and 40 ml of 30% hydrochloric acid is added. The beaker is left undisturbed overnight to allow the reaction to fully occur. Following this reaction, distilled water is added up to the 500 ml mark, the solution is stirred and allowed to settle overnight. The clear top layer is decanted, and this rinsing process is repeated to ensure the removal of any impurities. After the impurities are removed, the sample is dried on a hot plate and then placed in an oven preheated to 60°C for an additional 30 minutes. Once the drying process is complete, the sample is cooled for 20-25 minutes before being reweighed. The difference in weight between the initial and final measurements represents the carbonate content in the sample.

Silica content

Sediments were subjected to X-ray Fluorescence (XRF) test for the silica content analysis. For XRF sample preparation, the sediment samples were finely ground and mixed with a binder, such as boric acid, to form a uniform blend. This mixture was then compressed into pellets or tablets using an automatic press to ensure consistency across samples. Quality control procedures were followed to guarantee uniformity in sample preparation, and the samples were thoroughly dried to eliminate moisture. The prepared samples were then loaded into the XRF instrument, Rigaku ZSX Primus IV, which was calibrated using silica standards. XRF analysis was conducted, and the silica content was quantified using calibration curves. Throughout the process, strict adherence to safety protocols and manufacturer guidelines for instrument calibration and sample handling was maintained to ensure accurate and reliable results.

RESULTS AND DISCUSSION

Particle size distribution

The descriptive statistics of the particle size distribution of sediments collected from the nearshore beach areas of Kelantan and Terengganu are presented in **Table 1**, indicating the variability in sediment texture across different sampling locations. Silt and clay particles have a mean content of 15.62%, with a broad range from 0.30% to 94.40%, highlighting localized zones with high fine sediment accumulation. Very fine and fine sands also occur in substantial amounts, averaging 21.18% and 14.13%, respectively. Coarser fractions, such as gravel and very coarse sand, are less abundant, with mean values of 4.46% and 10.81%, respectively, but show high variability in certain samples. The median particle size (D_{50}) ranges from 17.16 µm to 1547.00 µm, reflecting a wide spectrum of sediment coarseness and energy zones.

To further interpret the statistical nature of the particle size distribution, skewness and kurtosis values are illustrated separately in **Figure 2**. As shown, the silt and clay distributions are highly skewed (skewness of 2.02) and leptokurtic (kurtosis of 3.55), suggesting a concentration of values towards lower percentages with occasional very high values. Very fine sand shows a slightly platykurtic distribution (kurtosis of -0.33), indicating a broader peak than a normal distribution, with a moderate skewness of 1.11. For fine sand, the skewness and kurtosis values suggest moderate variability, showing a particularly leptokurtic distribution (kurtosis of 3.86), indicative of peaked data. The coarsest fraction, gravel, has a high kurtosis (5.05) and skewness (2.28), indicating a peaked distribution.

Table 1: Summary of Descriptive Statistics of Particle Size Distribution of Sediments

Parameter	*Si & C*	*VFS*	*FS*	*MS*	*CS*	*VCS*	*G*	*Median D_{50}*
Mean	15.62	21.18	14.13	16.43	17.58	10.81	4.46	393.84
Range	94.10	90.67	74.80	78.49	82.00	75.90	44.20	1529.84
Minimum	0.30	0.03	0.20	0.10	0.00	0.00	0.00	17.16
Maximum	94.40	90.70	75.00	78.59	82.00	75.90	44.20	1547.00

Note: Si = Silt; C = Clay; VFS = Very Fine Sand; FS = Fine Sand; MS = Medium Sand; CS = Coarse Sand; VCS = Very Coarse Sand; G = Gravel

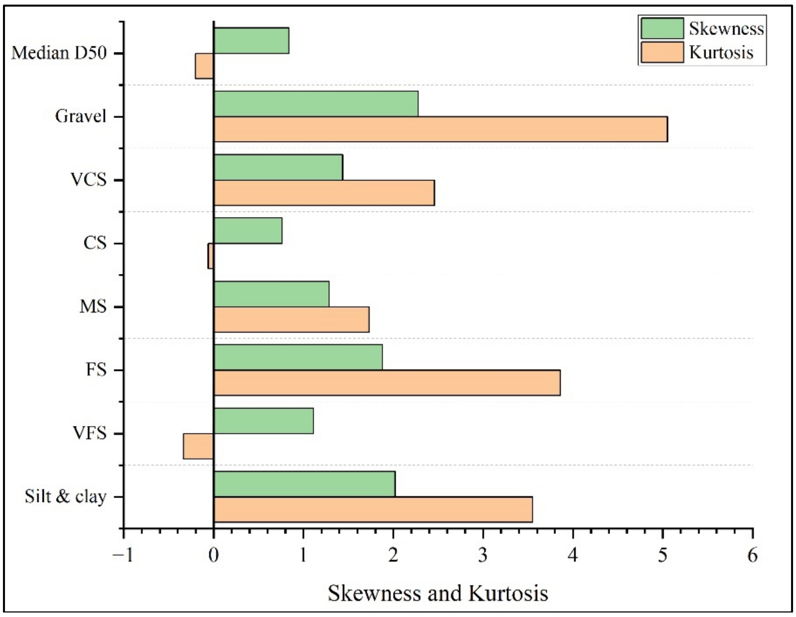

Figure 2. Skewness and Kurtosis of Particle Size Distribution of Sediments

The variability in particle size distribution suggests different depositional environments and energy conditions. The high skewness and kurtosis in silt & clay and gravel suggest localized areas with either very calm or very energetic conditions, respectively, which influence sediment deposition (Ikhane *et al*., 2019). The presence of significant very fine and fine sands across the samples could indicate predominant moderate-energy environments, typical of nearshore areas (Diaconeasa, 2018). The broad range in median particle sizes further supports the hypothesis of varying depositional settings across the sampled locations. Locations with smaller median sizes might be more sheltered or distal from sediment sources, while larger sizes could indicate proximal, higher-energy environments.

Classification of sediments

The Folk classification (Folk *et al*., 1970), as illustrated in **Figure 3**, showcases the texture of sediment samples from the nearshore areas of Kelantan and Terengganu, Malaysia, based on their grain size compositions. This classification is crucial for understanding the sedimentary environments and the depositional processes influencing sediment deposition (Folk *et al*., 1970). The most common sediment types identified were slightly gravelly sand ((g)s) and gravelly sand (gS), each constituting 19% of the samples. These sediments are indicative of high-energy environments where coarse materials such as gravel and sand are predominantly deposited. Such environments are typically associated with active wave and current actions, which are characteristic of open coastlines and nearshore zones where sediment dynamics are heavily influenced by tidal and wave activities. Muddy sand (mS) and slightly gravelly muddy sand ((g)mS), accounting for 12% and 11% of the samples respectively, suggest mixed-energy environments where finer materials are interspersed with coarser grains due to shifting energy conditions. Constant reworking of sediments by waves and currents likely prevents the formation of homogenous sediment layers (Ding *et al*., 2018). These sediment types often form in areas where tidal actions and river outflows dynamically alter the energy conditions, leading to the deposition of mixed sediments.

Less common but significant are the categories of sandy mud (sM) and slightly gravelly sandy mud ((g)sM), making up 4% and 5% of the samples, respectively. These categories reflect transitional environments where both sandy and muddy materials coexist, possibly influenced by fluctuating hydrodynamic conditions that prevent the formation of homogeneous sediment layers. The pure classes, such as sand (S), which alone accounts for 21% of the samples, highlight the dynamic nature of these coastal environments. The presence of sand in significant quantities indicates areas where finer materials are often washed away, leaving behind sand that is continuously reworked by waves and currents. This constant reworking creates a diverse range of sediment compositions and underscores the variable and complex nature of sediment deposition along the Kelantan and Terengganu coasts.

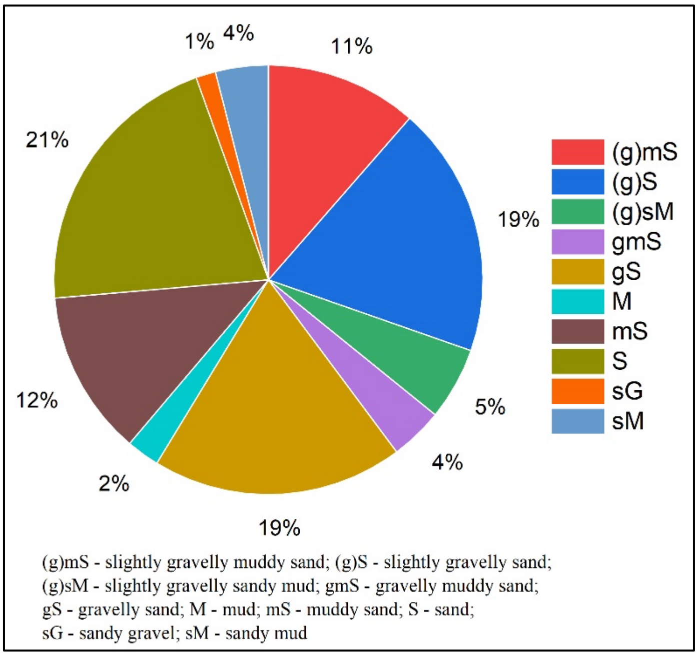

Figure 3. Folk Classification of Sediments

Textural characteristics & distribution symmetry

Figure 4 provides a comprehensive overview of the mean particle size distribution, sorting, skewness, and kurtosis of sediment samples from the nearshore areas of Kelantan and

Terengganu, Malaysia, each contributing to an understanding of the depositional environment and sediment dynamics.

The mean particle size data reveals a varied sediment composition, highlighting the dominance of very fine sand, which accounts for 28% of the samples, and coarse sand, comprising 33% of the samples. This suggests a broad range of energy environments; very fine sand is typically deposited under lower energy conditions, whereas coarse sand settles in higher energy environments. The presence of very coarse silt and fine sand in smaller quantities further underscores areas within the sampling domain where varying energy conditions influence sediment deposition (Ikhane *et al*., 2019). The sorting data indicates that most of the sediments are moderately sorted (33%) or poorly sorted (35%), which implies deposition in dynamic environments with fluctuating energy conditions, likely influenced by tidal currents, storm events, or riverine inputs (Ai *et al*., 2024). The presence of very well-sorted sediments (3%), although less common, suggests more stable and uniform depositional settings in certain areas. Skewness in the sediment distribution varies, with 37% of samples showing a symmetrical distribution, indicating a balanced mix of finer and coarser grains, typical of environments with moderate and intermittent energy. Additionally, fine-skewed (19%) and coarse-skewed (14%) distributions suggest localized influences such as wave or current patterns that preferentially sort particles by size. Kurtosis analysis shows a predominance of mesokurtic (20%) distributions, indicating a normal distribution of sediment sizes typical of mixed-energy environments. The occurrence of leptokurtic (12%) and very leptokurtic (15%) distributions reflects areas where specific grain sizes dominate, due to selective transport and deposition processes.

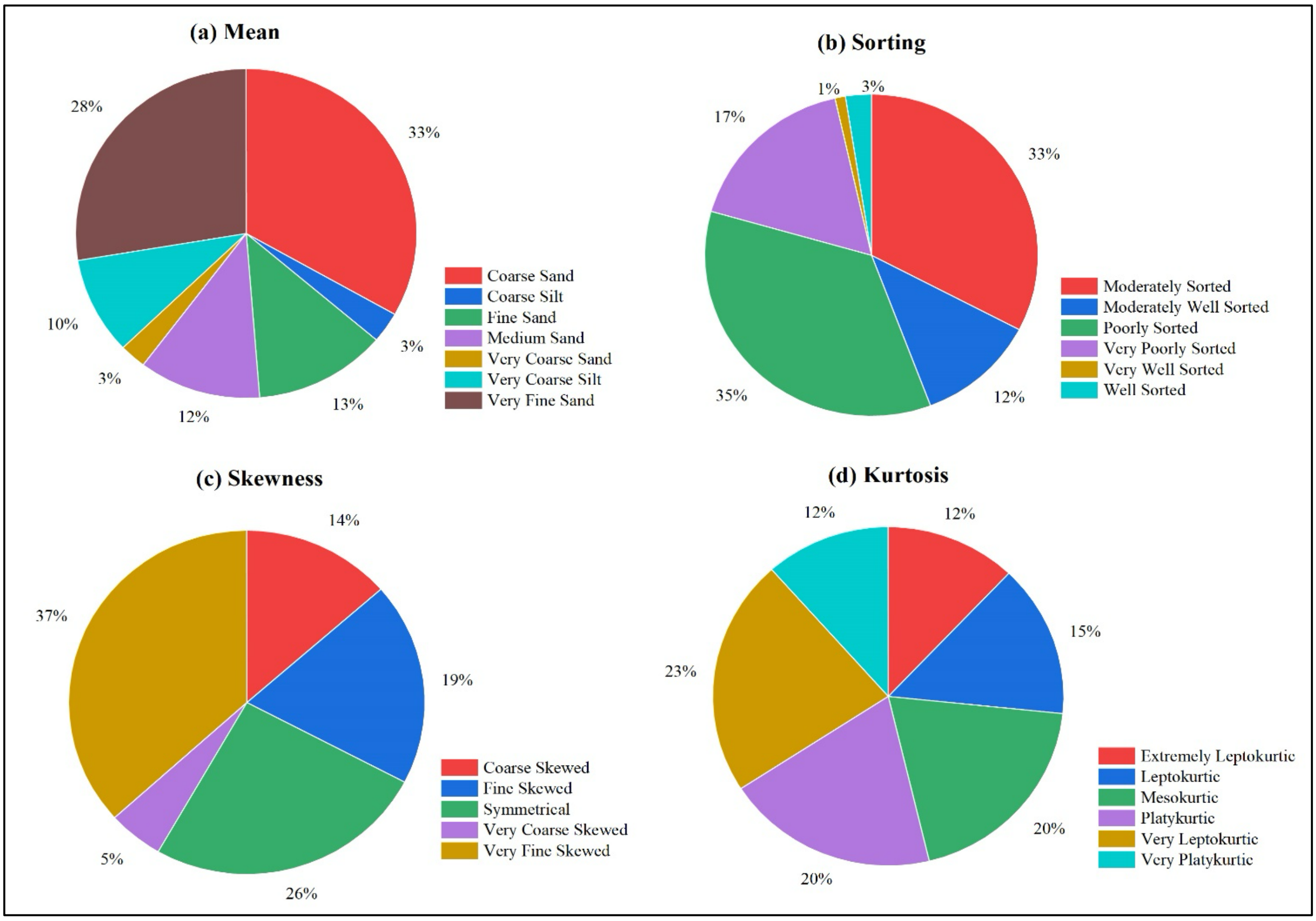

Figure 4. Overview of (a) Mean, (b) Sorting, (c) Skewness, and (d) Kurtosis of Sediment Samples

The data from **Figure 4** collectively point to a complex and dynamic sedimentary environment across the sampled regions. The prevalence of coarser grains along with poor sorting suggests that the sediments are influenced by a mixture of high-energy events and ongoing sediment reworking. This could be indicative of areas closer to river mouths or under the influence of strong marine currents that contribute to the heterogeneous nature of the sediment deposition (Thanh *et al*., 2017; Gemilang *et al*., 2018). The varied skewness and kurtosis across the samples further underscore the influence of intermittent and diverse depositional energies, reflecting both natural and potentially anthropogenic impacts on sediment dynamics (Anjum *et al*., 2018).

Carbonate and organic content

The descriptive statistics for carbonate and organic matter content across sediment samples offer valuable insights into the chemical composition and environmental conditions of the nearshore areas of Kelantan and Terengganu, Malaysia. The summary of descriptive statistics for carbonate and organic matter contents is represented in **Table 2**.

The average carbonate content is 15.39%, with a standard deviation of 8.95, indicating a moderate variability in carbonate levels across different samples. This suggests varying degrees of biogenic material contributions or differing levels of marine influence across the sampled sites. Carbonate content ranges from a minimum of 0.55% to a maximum of 52.8%, highlighting significant differences in the sedimentary environments, possibly influenced by factors such as proximity to coral reefs or other carbonate-producing organisms. The kurtosis value of 1.27 suggests a relatively flat distribution, whereas a skewness of 1.14 indicates a slight tail towards higher values, suggesting that some areas may have enhanced carbonate deposition. The mean organic matter content is relatively low at 0.83%, with a standard deviation of 1.21. This reflects the typical organic content expected in coastal sediments but shows that some areas might have limited organic deposition or that organic material is efficiently decomposed or diluted by inorganic sediments. Organic matter varies from 0% to 7.1%, indicating some areas with negligible organic deposits, which could be due to high rates of decomposition, dilution, or both. A high kurtosis value of 10.51 shows a very peaked distribution, and a skewness of 3.01 strongly indicates that most samples contain very low organic matter, with a few exceptions having higher concentrations, possibly linked to localized inputs or less dynamic water conditions allowing organic buildup.

Table 2: Summary of Descriptive Statistics of Carbonate and Organic Content of Sediments

Parameter	*Carbonate*	*Organic*
Mean	15.392	0.834
Standard Deviation	8.954	1.213
Sample Variance	80.177	1.471
Kurtosis	1.272	10.511
Skewness	1.138	3.013
Range	52.250	7.100
Minimum	0.550	0.000
Maximum	52.800	7.100

The variability in carbonate and organic matter content among the sediment samples can be attributed to a range of environmental and biological factors. The significant range in carbonate content might indicate different depositional settings, influenced by biological activity and water chemistry. High carbonate content in some samples could suggest proximity to coral reefs or areas with substantial shell debris (Jiangyong *et al*., 2011; Woodroffe *et al*., 2017). The low and highly variable organic matter content across the samples suggests that these nearshore environments might be subject to conditions that limit organic deposition, such as high-energy environments that prevent organic matter accumulation or high temperatures leading to rapid decomposition (Wu *et al*., 2024; Hanz *et al*., 2024). The few samples with higher organic content could be indicative of areas with more vegetative input or reduced hydrodynamic activity, allowing organic matter to accumulate.

Elements and oxides

The XRF analysis provides detailed insights into elemental and oxide composition of sediment samples, mineralogical and environmental processes influencing the coastal regions of Peninsular Malaysia. The elemental and oxide composition of a random sediment sample (C041) is represented in **Figure 5** and **6**, respectively, showing the dominance of Silicon (Si), Aluminium (Al), Calcium (Ca), and Iron (Fe) among the elements and Silica (SiO_2), Aluminium Oxide (Al_2O_3), Calcium Oxide (CaO), and Ferric Oxide (Fe_2O_3) among the oxides present in sediment samples.

Based on the dominance of these elements and oxides, summaries of descriptive statistics of elements and oxides in sediment samples are presented in **Tables 3** and **4**, respectively. The descriptive statistics illustrate significant variability and unique distribution patterns within the elemental and oxide contents, reflecting complex interactions between geological sources and environmental conditions in the sediment deposition areas. Si stands out with an average concentration of 39.46%, which corresponds closely with the dominant SiO_2 content of 85.11% in the oxide analysis. This high silicon content is indicative of quartz-rich sedimentary material, which is characteristic of coastal and sandy environments (Zhao *et al*., 2024). Ca and CaO show substantial concentrations of 7.46% and 10.20%, respectively, pointing to calcareous materials in the sediments, likely derived from shell fragments and coral detritus, which are common in marine sediments (Dampang *et al*., 2021). Al and Al_2O_3, with means of 0.76% and 1.49%, suggest the presence of aluminosilicate minerals typically associated with clay (Takematsu *et al*., 1993). This is further supported by the presence of terrigenous materials transported by rivers into the coastal zone. Fe and Fe_2O_3 are also significant, with average contents of 1.18% and 1.62%, respectively, indicative of iron oxides or hydroxides that are commonly found in both terrestrial and marine environments, often reflecting processes such as weathering, erosion, and sediment transport (Förstner, 2020).

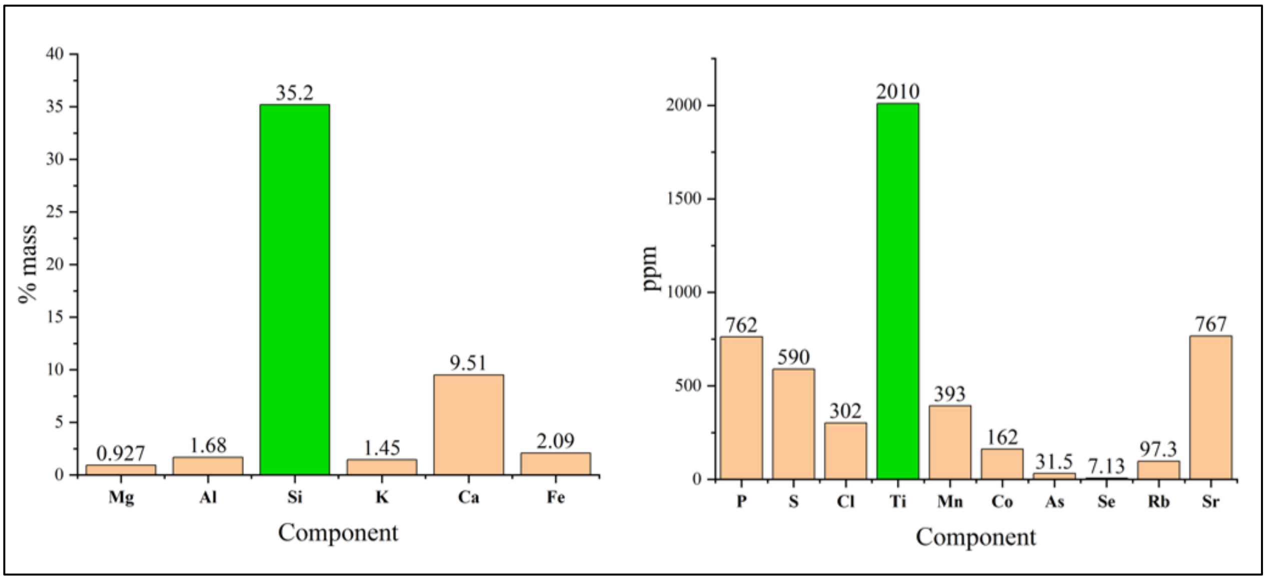

Figure 5. Elemental Composition of Sediment Sample (C041)

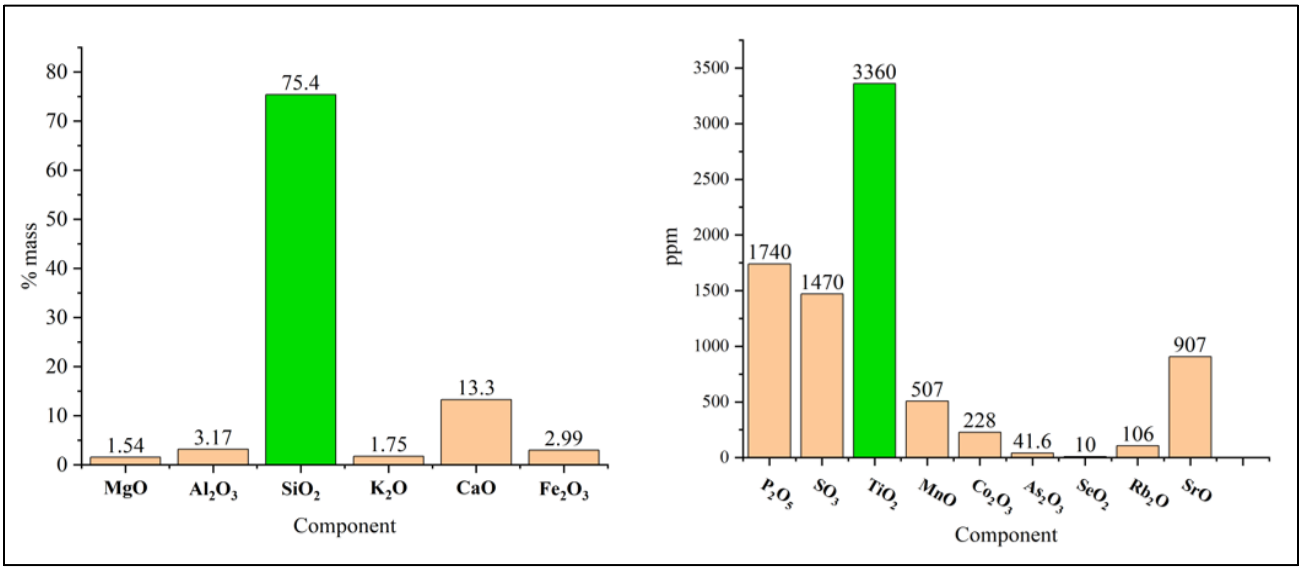

Figure 6. Oxide Composition of Sediment Sample (C041)

The considerable standard deviation observed for SiO_2 (13.31%) and CaO (13.38%) in the oxides and for Si (7.71%) and Ca (10.00%) in the elements suggests a high degree of variability in these components across different sediment samples. This could be due to the varying influences of hydrodynamic conditions, biological activity, and sediment source material. The skewness and kurtosis values highlight the non-uniform distribution of these components. Si shows a significant negative skewness (-2.19) coupled with a high kurtosis (4.10), suggesting a concentration of higher values with fewer low-value outliers, typical in environments with consistent geological inputs but occasional variations in depositional conditions. In contrast, Ca and CaO show a positive skewness (2.36 for Ca and similar trends for CaO), indicating a tendency towards higher concentrations in a subset of samples, which may be linked to localized biological processes or specific depositional environments such as coral reefs or shell-rich areas.

Table 3: Summary of Descriptive Statistics for Elements in Sediment Samples

Parameter	Al	Si	Ca	Fe
Mean	0.76	39.46	7.46	1.18
Standard Deviation	0.58	7.71	10.00	1.26
Sample Variance	0.33	59.40	99.91	1.58
Kurtosis	0.70	4.10	4.97	2.10
Skewness	1.33	-2.19	2.36	1.66
Range	1.99	31.80	40.50	5.01
Minimum	0.18	14.10	0.30	0.08
Maximum	2.17	45.90	40.80	5.09

Table 4: Summary of Descriptive Statistics for Oxides in Sediment Samples

Parameter	$Al2O_3$	SiO_2	CaO	Fe_2O_3
Mean	1.49	85.11	10.20	1.62
Standard Deviation	1.20	13.31	13.38	1.74
Sample Variance	1.43	177.16	179.02	3.03
Kurtosis	2.27	7.03	5.59	2.39
Skewness	1.63	-2.54	2.44	1.71
Range	5.39	68.10	56.80	7.15
Minimum	0.34	30.10	0.30	0.12
Maximum	5.73	98.20	57.10	7.27

Correlation analysis of sediment properties

The Pearson correlation analysis was carried out to determine the relationship between different sediment characteristics, including particle size fractions and key chemical properties. The Pearson correlation matrix is presented in **Figure 7**. A strong positive correlation value of 0.64 between silt & clay and organic content indicates that finer particles like silt and clay tend to accumulate more organic matter, likely due to their larger surface area, which traps organic materials. Similarly, a moderate positive correlation with R value of 0.319 between silt & clay and carbonate content suggests co-occurrence of these components in finer sediments, possibly through trapping mechanisms or biogenic processes. As sand particle size increases from fine to coarse, there is a noted decrease in both organic content and silica, reflected in their negative correlations. This pattern supports the idea that hydraulic sorting processes differentially deposit heavier mineral sands and lighter organic or siliceous materials (Motanated, 2014). Fine and very fine sand fractions show a slight positive correlation having R value of 0.101, indicating some degree of co-deposition or shared source materials. In terms of coarser materials, gravel shows positive correlations with coarse and very coarse sand, with R values of 0.298 and 0.456, respectively, highlighting similar depositional environments characterized by higher energy conditions necessary for these coarser particles to settle. A significant negative correlation of -0.476 between organic matter and silica underscores that biogenic and siliceous materials often accumulate in distinct environmental settings (Van Cappellen, 2003), while a positive correlation between organic and carbonate content having R value of 0.364, suggests co-deposition in specific areas where organic and carbonate-producing organisms are present.

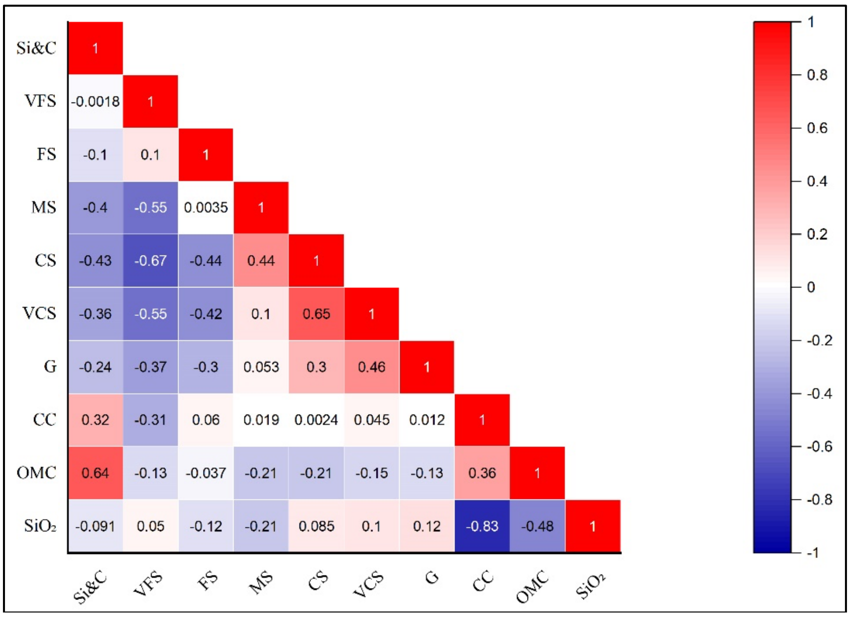

Figure 7. Pearson Correlation Matrix

These correlations provide valuable insights into the sedimentary processes and environmental settings of the sampled areas. The strong link between finer particles and higher organic and carbonate contents could be indicative of low-energy depositional environments where these materials can accumulate. In contrast, the negative correlation between larger sand particles and silica or organic content could point to differences in hydraulic sorting and depositional energy levels that influence where these materials are deposited. While the current study did not directly investigate the environmental factors, such as wave dynamics or riverine sediment loads, the observed trends align with established mechanisms in coastal sedimentology. The strong relationship between fine-textured sediments and organic content highlights the role of low-energy depositional environments. In such settings, reduced hydraulic energy allows for the settling and accumulation of finer particles, which, due to their larger surface area, efficiently trap and preserve organic matter (Puppin *et al*., 2025). Similarly, the moderate relationship between fine-textured sediments and carbonate content further suggests co-occurrence in low-energy zones, likely facilitated by biogenic processes and the accumulation of calcareous microorganisms (Trenggono *et al*., 2021).

Conversely, the negative correlation observed between increasing sand particle size and organic content aligns with hydrodynamic sorting. Heavier mineral sands are typically deposited under higher energy conditions, leading to a decrease in the lighter organic matter. Similarly, the relationship of gravel and coarse sand also implies high-energy conditions capable of transporting and depositing these coarser particles. These patterns suggest the influence of hydrodynamic sorting, river discharge, and possible biogenic inputs in shaping the sediment characteristics, supported by findings in topical coastal environments (Jiangyong et al., 2011)(Hernandez-Hinojosa *et al*., 2018)(Ai *et al*., 2024). These contextual factors, though not measured directly, provide a reasonable basis for understanding the spatial variability in the sediment composition.

CONCLUSION

This study provides a comprehensive analysis of surface sediments from the nearshore areas of Kelantan and Terengganu, revealing substantial spatial variability in textural and geochemical properties. Particle size analysis showed dominance of very fine to coarse sand, with occasional high silt and clay content, indicating the presence of both low and high-energy depositional environments, suggesting the influence of tidal currents, wave activity, and riverine inputs. Sediment classification using the Folk system confirmed that slightly gravelly sand, gravelly sand, and muddy sand were the most prevalent textural classes, supporting the interpretation of mixed-energy depositional settings.

The organic matter content was generally low and showed high skewness and kurtosis, suggesting selective accumulation in more sheltered or biogenically active zones. Whereas the carbonate content varied significantly across samples, with higher concentrations likely associated with biogenic input from shell fragments or coral sources. Elemental analysis using XRF revealed the dominance of silicon, calcium, and aluminium, with SiO_2 and CaO as the major oxides, reflecting quartz-rich mineralogy and calcareous material contributions. Correlation analysis further supported the relationships between finer fractions and higher organic or carbonate content, while coarser fractions correlated with lower organic levels, consistent with hydrodynamic sorting processes.

The findings demonstrate the complex interplay between sediment characteristics and their depositional environments, suggesting that both natural processes, such as riverine inputs and monsoonal influences, and anthropogenic activities significantly impact the seabed sediment composition of these coastal regions. This research not only advances our understanding of tropical coastal sediment dynamics but also provides crucial insights for environmental management and conservation initiatives, which are vital for the local economy and biodiversity conservation.

ACKNOWLEDGEMENTS

The authors declare that they have no known competing conflict(s) of interest. The authors wish to acknowledge Jabatan Mineral Dan Geosains, Malaysia, for funding this study under the project “National Offshore Sand Resources (NORS)”.

REFERENCES

Ahmad F., Mamat M., Rivaie M., & Abdullah K. 2012. Sediment variation along the east coast of Peninsular Malaysia. *Ecological Questions*, *16*, 99–108.

Ai L., Liu S., Cong S., Zhang H., Cao P., Wu K., Ye W., Mohamed C.A.R., & Shi X. 2024. Spatial variability of surface sediments in the Malacca strait and its implications for sedimentary environments. *Journal of Asian Earth Sciences*, *259*, 105922.

Anjum R., Tang Q., Collins A.L., Gao J., Long Y., Zhang X., He X., Shi Z., Wen A., & Wei J. 2018. Sedimentary chronology reinterpreted from Changshou Lake of the Three Gorges Reservoir Area reveals natural and anthropogenic controls on sediment production. *Environmental Science and Pollution Research*, *25*, 17620–17633.

Ariffin E.H., Mathew M.J., Yaacob R., Akhir M.F., Shaari H., Zulfakar M.S.Z., Sedrati M., & Awang N.A. 2018. Beach morphodynamic classification in different monsoon seasons at Terengganu beaches, Malaysia. *Journal of Sustainability Science and Management*, *13*(Special Issue 5), 65–74.

Barnard P.L., Foxgrover A.C., Elias E.P.L., Erikson L.H., Hein J.R., McGann M., Mizell K., Rosenbauer R.J., Swarzenski P.W., & Takesue R.K. 2013. Integration of bed characteristics, geochemical tracers, current measurements, and numerical modeling for assessing the provenance of beach sand in the San Francisco Bay Coastal System. *Marine Geology*, *345*, 181–206.

Bird E. 2008. Coastal geomorphology: an introduction. *Jon Wiley & Sons Ltd*.

Carr M.H., Neigel J.E., Estes J.A., Andelman S., Warner R.R., & Largier J.L. 2003. Comparing marine and terrestrial ecosystems: implications for the design of coastal marine reserves. *Ecological Applications*, *13*(sp1), 90–107.

Dampang S., Purwanti E., Destyorini F., Kurniawan S.B., Abdullah S.R.S., & Imron M.F. 2021. Analysis of optimum temperature and calcination time in the production of CaO using seashells waste as $CaCO_3$ source. *Journal of Ecological Engineering*, *22*(5), 221–228.

Diaconeasa D.I. (2018). Granulometry of Sediments in the Mamaia Bay Area. *Diversity in Coastal Marine Sciences: Historical Perspectives and Contemporary Research of Geology, Physics, Chemistry, Biology, and Remote Sensing*, 133–140.

Ding W., Wu T., Qin B., Lin Y., & Wang H. 2018. Features and impacts of currents and waves on sediment resuspension in a large shallow lake in China. *Environmental Science and Pollution Research*, *25*, 36341–36354.

El Idrissi S., Labriki A., Sadiki M., Akhlidej N., Bounouira H., Said S., Amsil H., Didi A., Aarab I., & Chakiri S. 2024. Geochemical Analysis of Coastal Sediments near Larache and Moulay Bousselham, Morocco. *Ecological Engineering & Environmental Technology (EEET)*, *25*(8).

Esen, E., Kucuksezgin, F., & Uluturhan, E. (2010). Assessment of trace metal pollution in surface sediments of Nemrut Bay, Aegean Sea. *Environmental Monitoring and Assessment*, *160*, 257–266.

Folk R.L., Andrews P.B., & Lewis, D.W. 1970. Detrital sedimentary rock classification and nomenclature for use in new zealand. *New Zealand Journal of Geology and Geophysics*, *13*(4), 937–968.

Förstner U. 2020. Inorganic sediment chemistry and elemental speciation. In *Sediments* (pp. 61–105). CRC Press.

Garzanti E., & Resentini A. 2016. Provenance control on chemical indices of weathering (Taiwan river sands). *Sedimentary Geology*, *336*, 81–95.

Gemilang W.A., Wisha U.J., & Rahmawan G.A. 2018. Particle size characteristics of riverbed sediments transported by tidal bore 'BONO'in Kampar Estuary, Riau-Indonesia. *Mar. Res. Indones*, *43*, 25–35.

Guo Y., Yang S., Su N., Li C., Yin, P. & Wang Z. 2018. Revisiting the effects of hydrodynamic sorting and sedimentary recycling on chemical weathering indices. *Geochimica et Cosmochimica Acta*, *227*, 48–63.

Hanz U., Wei B., Fovonova V., Sander L., Kopte R., Schröder H., Kasten S., & Holtappels M. 2024. *Particulate organic carbon dynamics of a depositional area in a high-energy shelf environment*. EGU General Assembly 2024.

Hernandez-Hinojosa V., Montiel-Garcia P.C., Armstrong-Altrin J.S., Nagarajan R., & Kasper-Zubillaga J.J. 2018. Textural and geochemical characteristics of beach sands along the western Gulf of Mexico, Mexico. *Carpathian J Earth Environ Sci*, *13*(1), 161–174.

Hossain M.N., Rahaman A., Hasan M.J., Uddin M.M., Khatun N., & Shamsuddin, S.M. 2021. Comparative seasonal assessment of pollution and health risks associated with heavy metals in water, sediment and Fish of Buriganga and Turag River in Dhaka City, Bangladesh. *SN Applied Sciences*, *3*, 1–16.

Ikhane P.R., Oladipo O.V., & Oyebolu O.O. 2019. Predicting the depositional environments and transportation mechanisms of sediments using granulometric parameters, bivariate and multivariate analyses. *GeoScience Engineering*, *65*(1), 11–28.

Jarmalavičius D., Žilinskas G., & Pupienis D. 2017. Geologic framework as a factor controlling coastal morphometry and dynamics. Curonian Spit, Lithuania. *International Journal of Sediment Research*, *32*(4), 597–603.

Jiangyong Z., Xuechao P., Yulan Z., & Yingmi W. 2011. Distribution of carbonate content in surface sediment from north of Zhongsha Islands to Northern slope in the South China Sea. *Tropical Geography*, *31*(2), 125–132.

Karlonienė D., Pupienis D., Jarmalavičius D., Dubikaltienė A., & Žilinskas G. 2021. Lithological and geochemical analyses of sandy beach sediments of different geological frameworks: the south-eastern Baltic Sea (Lithuania). *Arabian Journal of Geosciences*, *14*, 1–14.

Kolarova N., & Napiórkowski P. 2021. Trace elements in aquatic environment. Origin, distribution, assessment and toxicity effect for the aquatic biota. *Ecohydrology & Hydrobiology*, *21*(4), 655–668.

Ling, S.Y., Junaidi A., Harun A.M., & Baba M. 2022. Geochemical assessment of heavy metal contamination in coastal sediment cores from usukan beach, Kota Belud, Sabah, Malaysia. *Journal of Physics: Conference Series*, *2314*(1), 12008.

Liu L., Jiang G., Mao X., Zhao H., Zhao Y., Li Y., Zhao H., & Bi, Z. 2022. Geochemical Composition of Surface Sediments in the Bashang Area, North China and its Environmental Significance. *Frontiers in Earth Science*, *10*, 891032.

Lupker M., France-Lanord C., Galy V., Lavé J., Gaillardet J., Gajurel A. P., Guilmette C., Rahman M., Singh S.K., & Sinha R. 2012. Predominant floodplain over mountain weathering of Himalayan sediments (Ganga basin). *Geochimica et Cosmochimica Acta*, *84*, 410–432.

Ma K., Hu S., Wang T., Zhang B., Qin S., Shi S., Wang K., & Qingyu, H. 2017. Sedimentary environments and mechanisms of organic matter enrichment in the Mesoproterozoic Hongshuizhuang Formation of northern China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *475*, 176–187.

Motanated K. 2014. *Mechanisms of Sedimentation Inferred from Quantitative Characteristics of Heavy and Light Minerals Sorting and Abundance* [Texas A&M University]. https://hdl.handle.net/1969.1/153560

Nunes M., & Leston S. 2022. Coastal pollution: an overview. *Life Below Water*, 155–166.

Ouillon S. 2018. Why and how do we study sediment transport? Focus on coastal zones and ongoing methods. In *Water (Switzerland)* (Vol. 10, Issue 4, p. 390).

Paul K.M., van Helmond NA. G.M., Slomp C.P., & Jilbert T. 2024. Trace metals in coastal marine sediments: Natural and anthropogenic sources, correlation matrices, and proxy potentials. *Science of the Total Environment*, 175789.

Pupienis D., Buynevich I., Ryabchuk D., Jarmalavičius D., Žilinskas G., Fedorovič J., Kovaleva O., Sergeev A., & Cichoń-Pupienis A. 2017. Spatial patterns in heavy-mineral concentrations along the Curonian Spit coast, southeastern Baltic Sea. *Estuarine, Coastal and Shelf Science*, *195*, 41–50.

Ra K., Kim E.-S., Kim K.-T., Kim J.-K., Lee J.-M., & Choi, J.-Y. 2013. Assessment of heavy metal contamination and its ecological risk in the surface sediments along the coast of Korea. *Journal of Coastal Research*, *65*, 105–110.

Rezaee Ebrahim Saraee K., Abdi M.R., Naghavi K., Saion E., Shafaei M.A., & Soltani N. 2011. Distribution of heavy metals in surface sediments from the South China Sea ecosystem, Malaysia. *Environmental Monitoring and Assessment*, *183*, 545–554.

Rezaee K., Abdi M., Saion E., Naghavi K., & Shafaei M. 2011. Distribution of trace elements in the marine sediments along the South China Sea, Malaysia. *Journal of Radioanalytical and Nuclear Chemistry*, *287*(3), 733–740.

Saha S., Banerjee S., Burley S.D., Ghosh A., & Saraswati P.K. 2010. The influence of flood basaltic source terrains on the efficiency of tectonic setting discrimination diagrams: an example from the Gulf of Khambhat, western India. *Sedimentary Geology*, *228*(1–2), 1–13.

Sany B.T., Sulaiman A.H., Monazami G.H., & Salleh, A. 2011. Assessment of Sediment Quality According to heavy metal status in the West Port of Malaysia. *International Journal of Geological and Environmental Engineering*, *5*(2), 111–115.

Shaari H., Mohamad Azmi S.N.H., Sultan K., Bidai J., & Mohamad Y. 2015. Spatial Distribution of Selected Heavy Metals in Surface Sediments of the EEZ of the East Coast of Peninsular Malaysia. *International Journal of Oceanography*, *2015*(1), 1–10.

Shaari H., Mohd Nasir Q., Pan H.-J., Mohamed CA. R., Yusoff A.H., Wan Mohd Khalik W.M.A., Naim E., Setiawan R.Y., & Anthony E.J. 2020. Sedimentation and sediment geochemistry in a tropical mangrove channel meander, Sungai Kerteh, Peninsular Malaysia. *Progress in Earth and Planetary Science*, *7*, 1–11.

Skurzyński J., Jary Z., Kenis P., Kubik,R., Moska P., Raczyk J., & Seul C. 2020. Geochemistry and mineralogy of the Late Pleistocene loess-palaeosol sequence in Złota (near Sandomierz, Poland): Implications for weathering, sedimentary recycling and provenance. *Geoderma*, *375*, 114459.

Takematsu N., Sato Y., Kato Y., & Okabe S. 1993. Factors regulating the distribution of elements in marine sediments predicted by a simulation model. *Journal of Oceanography*, *49*, 425–441.

Thanh N.T., Stattegger K., Unverricht D., Nittrouer C., Van Phach P., Liu P., DeMaster D., Dung B.V., & Dong M.D. 2017. Surface sediment grain-size distribution and sediment transport in the subaqueous Mekong Delta, Vietnam. *Vietnam Journal of Earth Sciences*, *39*(3), 193–209.

Van Cappellen P. 2003. Biomineralization and global biogeochemical cycles. *Reviews in Mineralogy and Geochemistry*, *54*(1), 357–381.

Vetrimurugan E., Shruti V.C., Jonathan M.P., Roy P.D., Kunene N.W., & Villegas L.E.C. 2017. Metal concentration in the tourist beaches of South Durban: an industrial hub of South Africa. *Marine Pollution Bulletin*, *117*(1–2), 538–546.

Wittkop C., Bartley J.K., Krueger R., Bouvier A., Georg R.B., Knaeble A.R., Clair K.S., Piper C., & Breckenridge A. 2020. Influence of provenance and transport process on the geochemistry and radiogenic (Hf, Nd, and Sr) isotopic composition of Pleistocene glacial sediments, Minnesota, USA. *Chemical Geology*, *532*, 119390.

Woodroffe C.D., Farrell J.W., Hall F.R., & Harris P.T. 2017. Calcium Carbonate Production and Contribution to Coastal Sediments. In *The First Global Integrated Marine Assessment* (pp. 149–158). Cambridge University Press.

Wu G., Yang B., Nierop K., Reichart G.-J., Gebert J., & Kraal P. 2024. *Organic carbon burial and degradation in estuarine sediments in Europe's largest port area (Port of Rotterdam, The Netherlands)*. EGU General Assembly 2024.

Yalcin M.G., Setti M., Karakaya F., Sacchi E., & Ilbeyli N. 2015. Geochemical and mineralogical characteristics of beach sediments along the coast between Alanya and Silifke (Southern Turkey). *Clay Minerals*, *50*(2), 233–248.

Yang H.F., Yang S.L., Xu K.H., Milliman J.D., Wang H., Yang Z., Chen Z., & Zhang C.Y. 2018. Human impacts on sediment in the Yangtze River: A review and new perspectives. *Global and Planetary Change*, *162*, 8–17.

Yap C.K., & Pang B.H. 2011. Assessment of Cu, Pb, and Zn contamination in sediment of north western Peninsular Malaysia by using sediment quality values and different geochemical indices. *Environmental Monitoring and Assessment*, *183*, 23–39.

Zhao X., Song Z., Van Zwieten L., Wang Y., Ran X., Hao Q., Zhang J., Li Z., Sun J., & Wei Y. 2024. Silicon fractionations in coastal wetland sediments: Implications for biogeochemical silicon cycling. *Science of The Total Environment*, *912*, 169206.

Zonneveld K.A.F., Versteegh G.J.M., Kasten S., Eglinton T.I., Emeis K.-C., Huguet C., Koch B.P., de Lange G. J., de Leeuw J.W., & Middelburg J.J. 2010. Selective preservation of organic matter in marine environments; processes and impact on the sedimentary record. *Biogeosciences*, *7*(2), 483–511.