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Environmental dynamics in the tropical tourist beaches of southwestern India

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ABSTRACT

Tropical beaches and adjoining lush green vegetation areas are the preferred choices of recreation-leisure activities. The south-western coast of India is characterized by rainforests meeting serene beach profiles, with many aesthetic beach resorts. Though promoting economic prosperity, proliferation of recreational activities brings in unintended and irreversible adverse impacts to the coastal environment. A systematic documentation of field conditions of coastal environmental-landuse/landcover change, sediment textural properties and environmental dynamics may help assess sustenance of habitability of such popular tourist beaches. Four selected beaches of Kerala State, southwestern India, namely Pozhikkara, Hawa, Lighthouse and Chowara were studied in terms of pristine nature of geomorphology, beach profile, land use/land cover, sediment textural characteristics. The sediment textural characteristics indicate survival of only the medium-coarse sediments, occurrences of heavy minerals in majority of the samples, absence of spatial variability of sediment characteristics and prevalence of platykurtic nature, evidencing the anthropogenic interventions that caused monotony. While the sediments retain their affinity to marine signature, after transformation from fluvial origin, environmental discrimination diagrams show that majority of the studied sediments correspond to turbid-higher energy conditions and affirm the interpretation of anthropogenic impact on sediment texture. These results implicate that the recreational and associated commercial / constructional activities unto the intertidal region have heavily impacted the natural environmental conditions of beach ecosystem that gets further aggravated by flouting of coastal environmental regulations. Sustaining the recreational activity along the popular beach and habitability is under threats that require appropriate remedial-reclamation measures.

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Research Highlights

- Coastal environments facing adverse impacts from recreational activities
- Analysis of coastal environment and dynamics in popular beaches of Kerala
- Activities in intertidal regions heavily impacted the natural environmental conditions of beach ecosystem

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1 Introduction

Coastal regions form the intersection where Earth's natural processes converge with human habitation (Ramesh et al., 2015). A comprehensive understanding of beach dynamics and their evolution necessitates a thorough knowledge of the natural factors that interact across the various morphological zones of the beach, including the subtidal, intertidal, and supratidal areas (Nmiss et al., 2024). The World Bank reports that 75% of the world's major cities and 70% of its industrial capital and population are situated within 100 km of the coast (Liu et al., 2020). Numerous prominent global cities, such as Dhaka, Mumbai, Karachi, Kolkata, Lagos, Manila, Miami, New York, and Shanghai are situated in low-lying coastal zones (Von Glasow et al., 2013). These areas accommodate about 37% of the world's population and have a population density twice the global average (UNEP, 2025). The exploitation and utilisation of coastal zones significantly affect the sustainable development of coastal cities (Wei et al., 2021). Increased urbanisation in coastal regions leads to human-induced environmental changes, making these areas more prone to natural and anthropogenic hazards (Saxena et al., 2013). Global disaster statistics indicate that between 1975 and 2022, the number of reported disasters and affected individuals in coastal areas rose nearly fivefold, resulting in substantial economic losses (https://www.emdat.be/ accessed on 20.03.2025). The Intergovernmental Panel on Climate Change (IPCC) forecasts that by the end of this century, sea levels could rise by up to 1.1 m due to the accelerated melting of polar ice caps. Consequently, severe flooding events may become more frequent in low-lying coastal settlements, potentially impacting around 190 million people (World Bank estimates). Long-term planning for protection of settlements and other infrastructure in the shoreline regions requires an understanding of movement of sediment in the nearshore environment (Saravanan and Chandrasekar, 2010).

In addition to the evergreen search of pristine natural landscapes for recreational activities, when compared with the thickly populated-polluted-altered coastal regions, serene, lush-green covered rain forested beaches have always been preferred choice of tourist destination for any international traveller. Although tourists have diverse preferences, pristine beaches with sands and picturesque surroundings are highly favoured. This endeavour spans from west to east, all along the globe, especially near the equatorial, tropical forested beaches and thus beach tourism flourished and triggered associated growth of support industries, and urbanisation (Nagarajan et al., 2018; Pian et al., 2018; Ramkumar et al., 2018). The exponential growth of coastal tourism over the past 40 years has been a key driver of urban infrastructure development in majority of the coastal regions that led to various environmental challenges (Hall, 2001; Ghosh and Datta, 2012). Due to seasonal variations in the intensity of tourist impacts, the effects of human disturbances on sandy beaches have a strong seasonal impact (Brown and McLachlan, 2002). Though all the coastal beaches form interfaces between litho-hydro-atmosphere, the sandy beaches are highly susceptible/vulnerable to physical, chemical and biological interventions emanating from anthropogenic activities (Ramkumar et al., 2018). Thus, analysing long-term variations in beach processes is essential for identifying locations that require permanent protection and management interventions (Sreekala et al., 1998).

Coastal sediment plays crucial role in supporting aquatic and marine life within coastal ecosystems. However, urbanization, recreational activities and economic growth in the coastal regions have destructed the natural processes and contributed to environmental problems on a global scale (Vu, 2018). A systematic analysis of coastal sediments is crucial for understanding the dynamic interactions between land and sea, which are vital for maintaining the health and sustainability of coastal environments. It is essential for managing coastal erosion, protecting infrastructure, and preserving natural habitats. Statistical analysis of beach sediments provides insights into their inherent characteristics and depositional environment (Komar and Inman, 1970; Dora et al., 2011). Systematic study of the textural composition, distribution, and movement of sediments, sediment sources, depositional environments, nature of sediment remobilization, temporal accretion-erosion sites, and change in the sea levels due to climate change and/or hydrodynamic modifications in the dynamic coastal regions could be assessed (Sinha et al., 2021). The coastal sediment analysis provides valuable insights for sustainable coastal development at local to regional scale and contributes towards a better and habitable earth.

By recognising the importance of coastal sediment analysis in tourist beaches, Ghosh and Datta (2012) raised concern on the environmental status of Kovalam and suggested systematic assessment of impact of tourism to protect the beach ecosystem. Ramkumar et al. (2023) documented bulk geochemical and mineralogical characteristics of Kovalam beach sediment samples to evaluate the environmental status and associated risks. In this paper, we have documented the textural properties of sediments collected in the famous tourist beaches in Kerala with a view to identify prevalent environmental, natural and anthropogenic impacts and to constrain on the sustainable recreational habitability of the beach ecosystem.

2 Study area

The tourist beaches namely the Lighthouse, the Hawa, the Pozhikkara, and the Chowara, located in the Thiruvananthapuram District, southwestern India, frequented by international, national, regional and local visitors were selected for the present study (Fig. 1). These are located between latitudes 8°21′29.21″ N and 8°26′22.82″ N; longitudes 76°57′27.69″ E and 77°10′44.34″ E in the southern part of Kerala State, bordered by the Arabian Sea to the west and the Western Ghats to the east. The landscape of Kerala is drained by about 40 west flowing, medium and/or minor rivers, which transport sediments derived from both laterites and bedrock. These materials become admixed with and are eventually deposited in the lower reaches of the rivers (Babu et al., 2023).

Sea breeze circulation is prevalent along the Kerala coast during both the pre-monsoon and post monsoon seasons (Aparna et al., 2005; Subrahamanyam et al., 2001; Abdulla et al., 2023). Tropical cyclones in the Arabian Sea typically form during the pre-monsoon and post-monsoon seasons (Al-Manji et al., 2021; Abdulla et al., 2023). Most cyclones have traversed the offshore regions of the Kerala Coast (Sanap et al., 2020). The offshore region experiences 99th percentile wind speeds of approximately 9–10 m/s during the pre-monsoon and post-monsoon seasons, whereas during the southwest monsoon, wind speeds increase to around 11–14 m/s (Abdulla et al., 2023).

The primary morphological features along the coastline include coastal plains, barrier beaches/spits, pocket beaches, and cliffs/promontories (Thankappan et al., 2018; Pradeep et al., 2022). A rocky cliff extends along the Vizhinjam–Kovalam beach section and a lateritic cliff reaching an elevation of 50 m is present at Chowara (Pradeep et al., 2022). All these beach stretches are under a micro-tidal regime (Pradeep et al., 2022). During the southwest monsoon, the coastal region of Kerala experiences high wave intensity (Shahul Hameed et al., 2007). The tropical maritime climate and scenic natural beaches make these places excellent locales for tourism. Among these four beaches, the northernmost beach Pozhikkara (P) is located at the confluence of the Killi River and the region is surrounded by several tourist resorts. Hawa (H) and Lighthouse (L) beaches are located near the biggest tourist destination in this area-Kovalam Town, which is located in the north of Vizhinjam port. The Chowara (C) Beach is located in the south of Vizhinjam port and is slightly away from the urban and tourist populations.

3 Methods and materials

Based on the field-scale geomorphology, recreational and other anthropogenic use and the natural landscape profiles, four beaches were selected for sampling. The samples were collected in a normal condition (non-monsoon season) using a transect perpendicular to the coastline from berm to low-tide waterline (Fig. 1). A total of 16 samples were collected in which three samples were collected from Lighthouse beach, four from Hawa beach, four from Pozhikkara beach, and five from Chowara beach (Fig. 1). Sediment samples were collected from visibly undisturbed part of the beach using uncontaminated plastic scoops and were transferred immediately to plastic zip-lock covers. Then the sample covers are labelled and transported to the laboratory and stored. Standard laboratory protocols in sample preprocessing and dry sieving method of textural analysis were conducted following the procedures detailed in Ramkumar et al. (2000). Accordingly, all the samples were thawed and allowed to reach ambient temperature before the sample processing. The sediment samples were washed with distilled water to remove sea salt followed by a drying treatment at 60 °C in an air-oven. Approximately 20 g of sediment sub-samples were taken after homogenising, coning and quartering. Acid treatments with H_2O_2, HNO_3 and HCl were then carried out to remove organic contents, oxides and carbonates. Then the samples were dry-sieved at $1/2\varphi$ intervals in a semi-automatic sieve-shaker and the weight of sediment fractions remaining in each of the sieve were measured, tabulated and graphical measures of mean size, standard deviation, skewness and kurtosis were computed.

Linear discriminant functions (LDF) after Sahu (1964) were used for the interpretation of depositional condition/setting/environment of beach sediments as provided herein:

Aeolian/beach

$$Y1 = -3.5688*Mz + 3.7016*SD - 2.0766*SK + 3.1135*K \quad (1)$$

If $Y1 \leq 2.7411$ aeolian If $Y \geq 12.7411$ is beach

Beach/shallow agitated water

$$Y2 = 15.6534*Mz + 65.709*SD + 18.1071\ SK + 18.504*K \quad (2)$$

If $Y2 \leq 65.365$ Beach; If $Y2 \geq 65.365$ shallow agitated marine

Shallow marine/fluvial environment

$$Y3 = 0.2852*Mz - 8.7604*SD - 4.8932*SK + 0.0482*K \quad (3)$$

If $Y3 \leq 7.5190$ Fluvial; If $Y3 \geq 7.5190$ Shallow marine

Fluvial/turbidity

$$Y4 = 0.7215*Mz + 0.4030*SD + 6.7322*SK + 5.2927*K \quad (4)$$

If $Y4 \leq 9.81$ Turbidity current; If $Y4 \leq 9.81$ Fluvial deposit.

If $Y1$ is less than -2.7411, it indicates aeolian deposition; if $Y2$ is greater than 65.3650, it indicates beach deposition; if $Y3$ is less than -7.419, it indicates a fluvial marine environment; and if $Y4$ is less than 10,000, it indicates a fluvial environment; if higher than 10,000, it indicates turbidity (Ayodele and Madukwe, 2019; Kasim et al., 2023). Selected discriminant diagrams for interpretation of depositional setting, environment of deposition, energy conditions, transport mode, and sediment textural maturity were

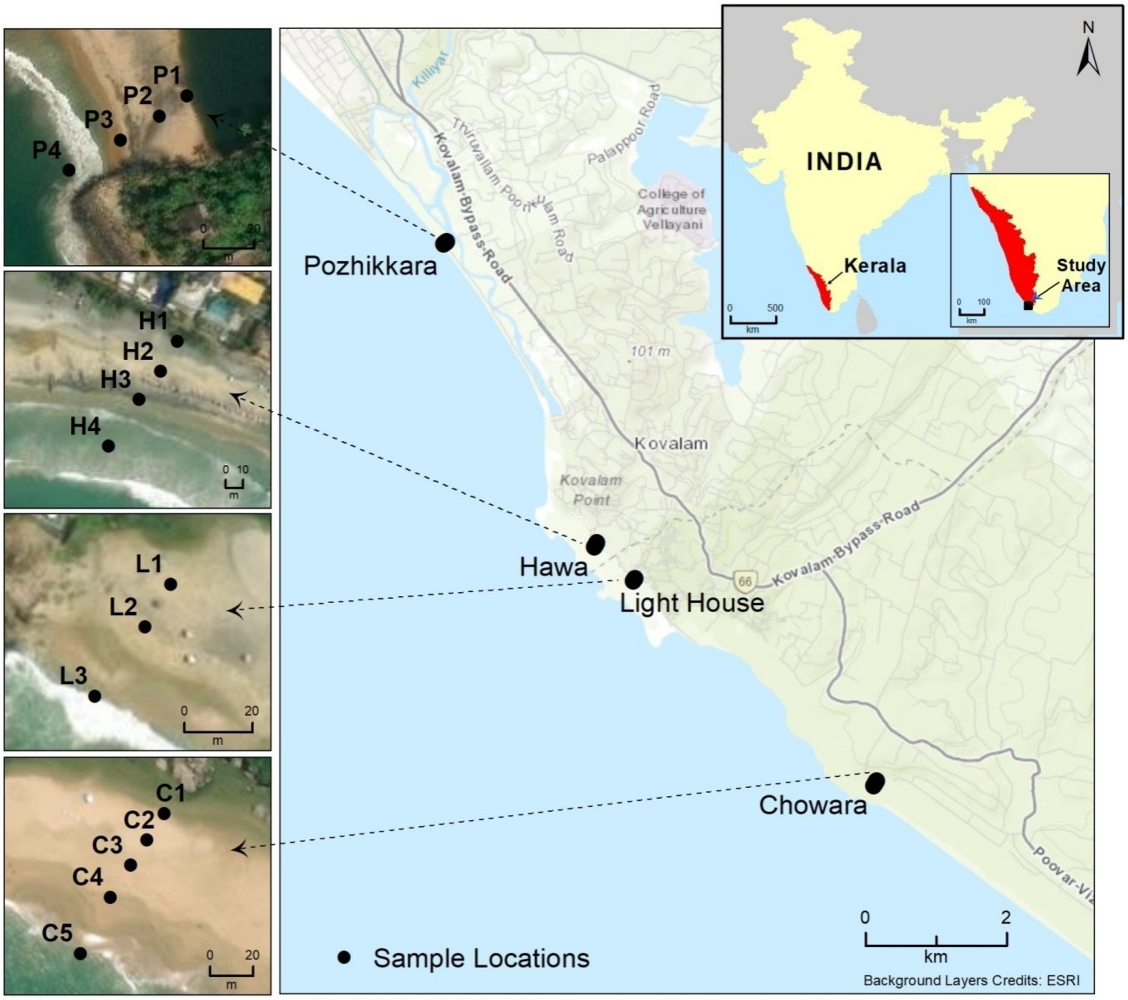

Fig. 1. Study area and sample locations. From north towards south, the beaches from where samples were collected are: Pozhikkara, Hawa, Lighthouse and Chowara. Inset images indicate the locales of sample collection for each of the beach.

employed for interpreting the graphical and statistical measures. The interpretations were further constrained toward enlisting of prevalent domination and or signatures of natural / oceanographic and anthropogenic actions based on which, attempts were made towards better understanding of ongoing environmental processes and management implications.

4 Results

4.1 Textural characteristics

The textural parameters and the results of linear discriminant functions of the studied sediments are presented in Table 1. The mean grain size (Mz expressed in φ units) varies from ~ -6.31 to 2.5, indicating that the sand grains are very coarse to medium in size. Sorting varies from well sorted (0.4) to extremely poorly sorted (>4), Kurtosis ranges from very platykurtic (0) to extremely leptokurtic (>3). Skewness varies from very coarse skewed (-0.97) to very fine skewed (0.55). Almost all the studied beaches resemble similar, although there are intersample variations within each of the beach from berm to low tide waterline.

Majority of the 16 sediment samples collected from 4 different beaches, fall within the riverine field (Fig. 2a and Fig. 2b) and only few samples of Chowara fall in the beach environment field. In addition, the Chowara samples show disparity from other beaches, in terms of affinity poor to good sorting while the samples from Pozhikkara, Hawa and Lighthouse fall in the field of good sorting. The bivariate plot of SD vs Mz (Fig. 2c) shows predomination of good sorting while few other samples are in the moderately good and poor sorting fields. The plot of MD vs SD shows majority of the samples in the river process field except

Location	Mz	SD	Sk	KG	*Y1*	*Y2*	*Y3*	*Y4*
L1	2.24	0.48	0.04	0.7	−4.121	80.281	−3.728	5.397
L2	2.5	0.4	−0.22	0.9	−4.182	78.087	−1.671	4.925
L3	2.22	0.47	0.02	0.74	−3.921	79.689	−3.546	5.464
H1	2.22	0.52	−0.06	0.79	−3.414	82.451	−3.591	5.169
H2	2.05	0.6	0.21	0.76	−3.165	89.381	−5.663	6.673
H3	1.91	0.67	0.26	0.666	−2.803	90.955	−6.565	6.383
H4	1.99	0.52	0.22	0.97	−2.614	87.252	−5.018	7.841
P1	−6.31	>4	−0.96	>3	260.112	2038.495	−145.648	273.921
P2	2.23	0.57	0.06	0.76	−3.607	87.511	−4.614	5.806
P3	1.55	0.54	0.55	1.17	−1.032	91.355	−6.923	10.796
P4	0	>4	−0.97	0	350.150	6162.377	−819.169	−44.432
C1	0.18	0.65	0.13	0.85	4.140	63.611	−6.238	5.242
C2	1.17	0.44	−0.28	2.06	4.448	80.275	−2.052	9.685
C3	0.31	0.72	0	0.77	3.956	66.411	−6.182	4.009
C4	0.52	1.17	−0.67	1.48	8.474	100.274	−6.752	3.226
C5	0.45	0.59	0.13	0.8	2.799	62.970	−5.638	5.196
Maximum	2.5	>4	0.55	>3	−4.182	62.970	−819.169	−44.432
Minimum	−6.31	0.4	−0.97	0	350.150	6162.377	−1.671	273.921
Mean	0.95	7.47	−0.09	4.28	37.82	583.83	−64.56	19.70

Table 1. **Computed textural measures and results of discriminant functions of the beach sediments. L:** Lighthouse; **H:** Hawa; **P:** Pozhikkara; **C:** Chowara; **Mz:** mean size; **SD:** Standard Deviation; **Sk:** Skewness; **KG:** Kurtosis.

the samples from the Chowara beach fall together in wave process field (Fig. 2d). The C=M pattern shows most of the samples and all Hawa samples in the rolling and suspension with rolling modes of transportation (Fig. 2e) while two samples from Lighthouse are in between graded suspension and uniform suspension, one sample from Pozhikkara fall in rolling and suspension mode of transportation, one sample from Chowara in rolling mode. Most of the samples from Hawa and Lighthouse are transported by graded and uniform suspension respectively. Though there are scatters, most of the samples fall in the river, although the samples from Chowara sample fall away from other locations when discrimination diagrams of textural properties are examined (Fig. 3a–d). The samples are scattered, which is coarse-fine sand and 4 samples are away from others (Fig. 3c). The Fig. 3e–g discriminated the channel, overbank, and overbank-pool deposits.

4.2 Linear discriminant function analysis

Based on the computed statistical parameters, the values of *Y1*, *Y2*, *Y3*, and *Y4* for all samples range from −4.182 to 350.150, 62.970 to 6162.377, −819.169 to −1.671, and −44.432 to 273.921 respectively (Table 1). The samples from Lighthouse and few samples from Pozhikkara (P2), Hawa (H1, H2, and H3), and only one sample (P3) from Pozhikkara showed values of *Y1* < -2.7411. All the samples from Chowara show *Y1* > -2.7411. The combined LDF plots of *Y1* vs *Y2*, *Y2* vs *Y3*, and *Y3* vs *Y4* suggest that the sediments are classified within the categories of shallow marine beach, turbidity current, and shallow marine environments (Fig. 4a–c), with the exception of P3, which falls within the fluvial/shallow marine category.

The bivariate plot of *Y2* vs *Y1* (Fig. 4a) showed the Chowara samples clustering together except C2 and C4 away from the other samples within the beach/shallow agitated water environment. In the *Y3* vs *Y2* (Fig. 4c) plot, the samples C1 and C5 together fall within the shallow marine/ beach field but the C2, C3, C4 are scattered in the shallow marine agitated environment. The samples from other three locations are clustered together within the shallow marine agitated environment.

4.3 Ground truth data on landuse and beach characteristics

In all the beaches surveyed and sampled, constructional—commercial—fishing-recreational activities within the region defined by coastal zone regulation act, and in certain regions up to the intertidal region were evidenced. Despite construction of protective walls by ripraps, the development of wave cut terraces, specific winnowing of finer sediments and enrichment of darker, heavy minerals within the beach profile, excessive sediment sourcing by shoreward migration of coastline, accumulation of solid and other wastes within the coastal zone are supply are also documented (Figs. 5 and 6) during field survey and sampling campaign.

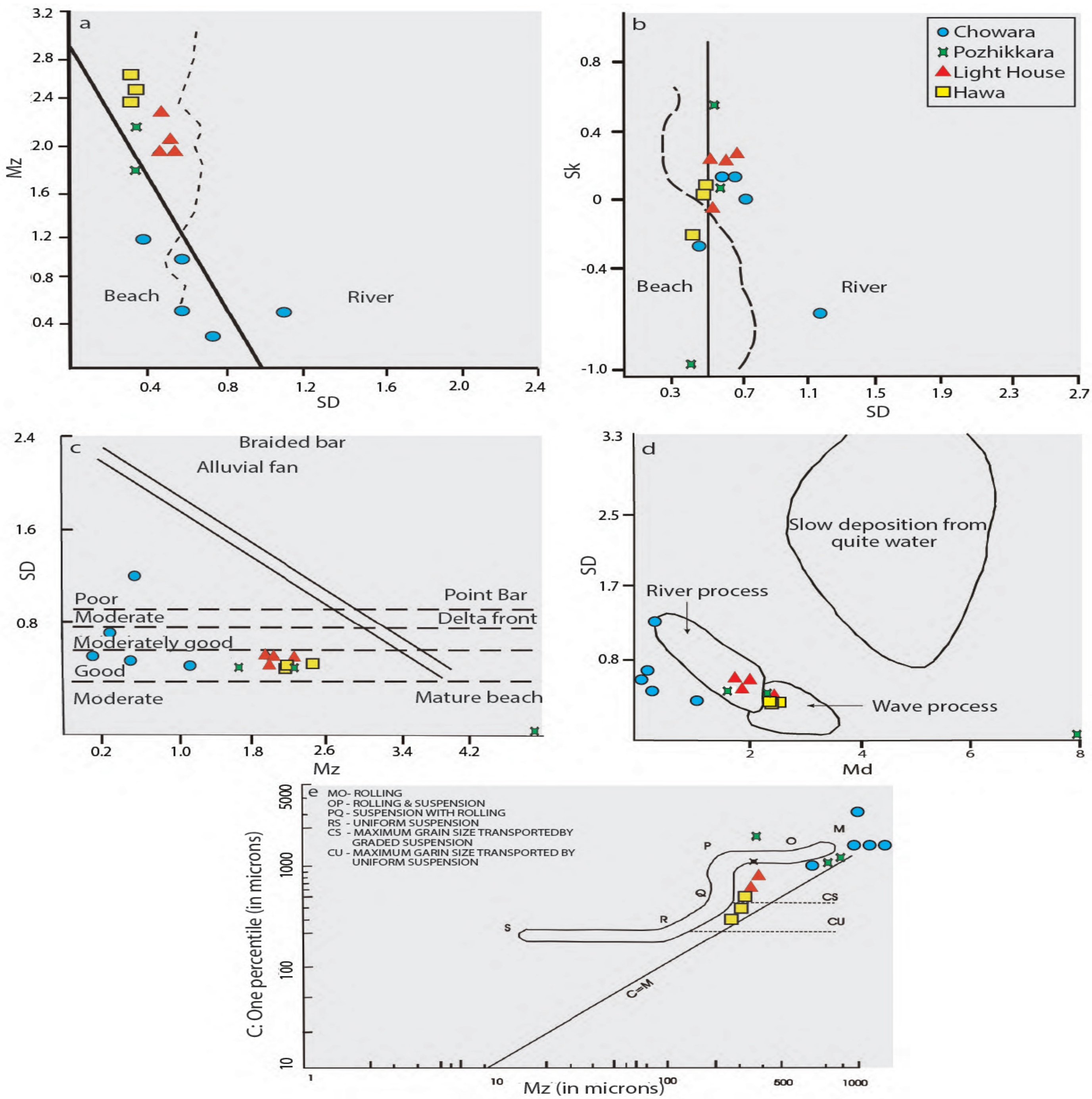

Fig. 2. Environmental interpretations based on textural parameters. (a) Discriminant diagram based on mean size (Mz) and standard deviation (SD) with discriminant lines of Glaister and Nelson (1974) (solid line) and Friedman (1967) (dashed line) differentiating the samples into beach and river sediments; (b) Bivariate plot of Skewness (Sk) Vs. Standard deviation (SD) with discriminant lines of Glaister and Nelson (1974) (solid line) and Friedman (1967) (dashed line) differentiating the samples into beach and river sediments; (c) Bivariate plot of Mean size (Mz) Vs. Standard deviation (SD) (after Glaister and Nelson, 1974); for discriminating maturity levels of sediments; (d) Bivariate plot (after Stewart Jr., 1958) of standard deviation (SD) Vs. median (Md) for discriminating the sediments deposited under low energy-quite water, unidirectional flow conditions-river and bidirectional agitated conditions—wave process; (e) Discriminant plot of modes of sediment transport (after Passega, 1964) based on Standard deviation (SD) Vs. Median (Md).

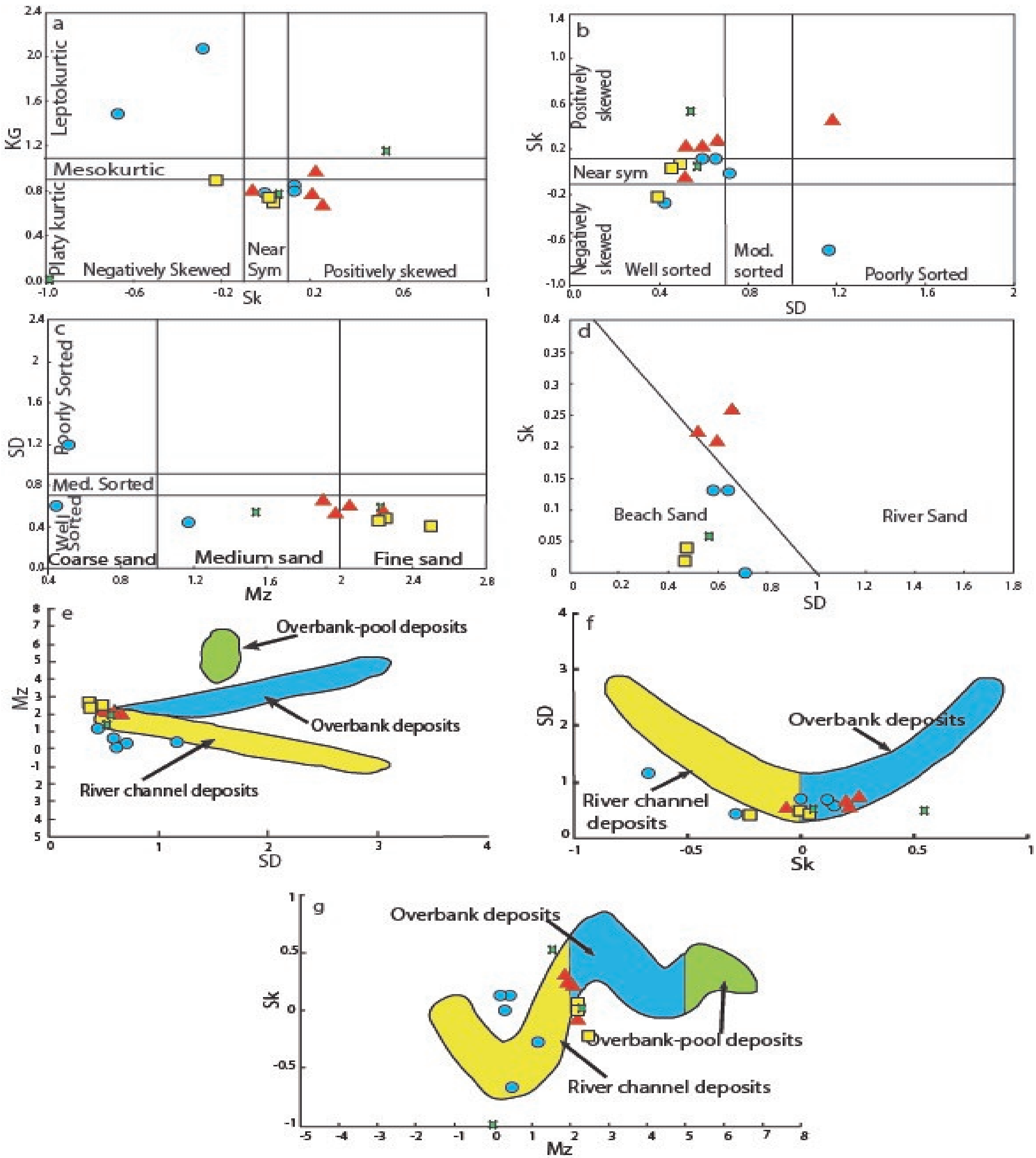

Fig. 3. Bivariate scatter plots of environmental discrimination and sediment characterization. (a) KG Vs. Sk; (b) Sk Vs. SD; (c) SD Vs. Mz; (d) Sk Vs. SD; (e) Mz Vs. SD; (f) SD Vs. Sk; (g) Sk Vs. Mz.

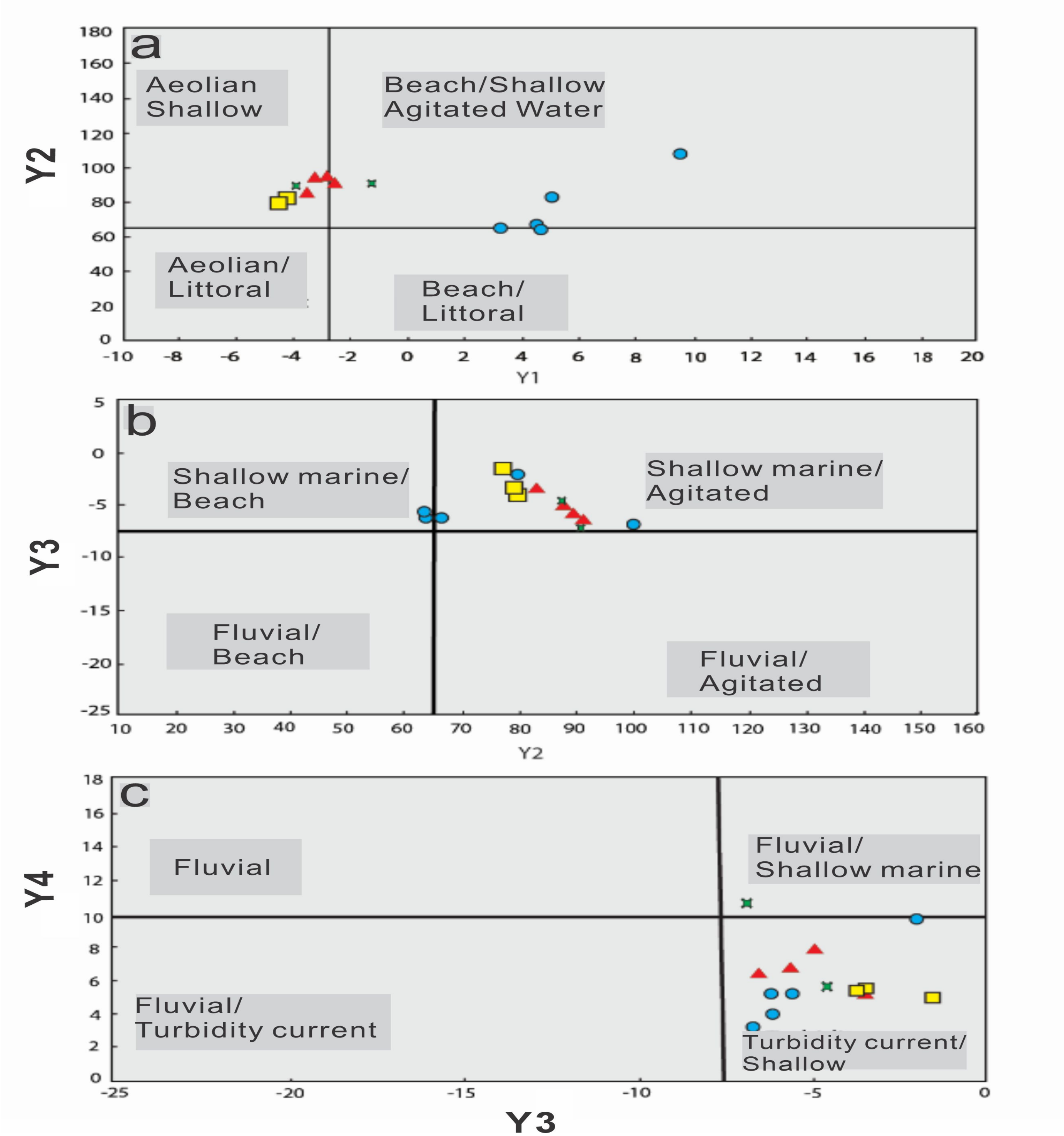

Fig. 4. Linear Discrimination Function (LDF) plots of environmental characterization. (a) Bivariate plot of *Y2* Vs. *Y1* shows the discriminant diagram for differentiating the samples into Aeolian/shallow, beach/shallow agitated water, aeolian/littoral environment, and beach/littoral; (b) Bivariate plot of *Y3* Vs. *Y2* differentiate shallow marine/beach, shallow marine/agitated, fluvial/beach, and fluvial/agitated environments; (c) Bivariate plot of *Y4* Vs. *Y3* for discriminating the sediments deposited under fluvial, fluvial/shallow marine, fluvial/turbidity current, and turbidity current/shallow conditions.

Fig. 5. Field characteristics of the coastal zone. (a) Panoramic view of the Lighthouse beach. High energy and erosional nature of the beach are evidenced by the dark coloured heavy mineral concentration, and occurrences of constructional activities within the hightide waterline flouting the coastal zone regulation can be evidenced from this field photograph; (b) Closeup view of the Lighthouse construction protected by riprap boulder wall against wave erosion. This is a vicious cycle, as could be visualized in combination with the photograph shown in "c" wherein destruction of natural vegetative cover and alternation of natural landscape profile/land cover by construction activities invigorate soil erosion and make the landscape highly susceptible to wave impact; (c) Construction activities alter the natural land cover irreversibly and invigorate soil erosion and supply sediments to the coastal zone in excess quantities that could not be reworked under normal oceanographic conditions, that in turn alter the coastal processes and nutrient cycles too; (d) *Ipomoea biloba* creeper, that once thrived in the beach ridge-swale complex and formed natural barrier for coastal erosion and promoted accretion, is currently under vanishing phase, and this change in landcover has contributed towards augmented erosion; (e) and (f) Improper waste management encourages contamination of coastal sediments with the modern pollutants including heavy metals and microplastics; (g) Freshwater influx through a backwater channel located in the Pozhikkara beach that supplies sediments and freshwater directly into the coastal region during low tides.

Fig. 6. Field characteristics of the coastal zone. (a) Channel incision that exposes the intertidal sediments that abut against artificially-protected wave-cut terrace. Note that only the darker, heavy mineral grains dominate the sedimentary record, which means prevalence of relatively higher energy conditions that selectively winnow away lighter minerals; (b) In addition to construction related interferences within the coastal zone, fishing activities related boat refuge add to the growing list of pollutants into the Chowara beach; (c) The non-existent beach in the Hawa beach, showing the testimony to the extent of landuse change and interference with coastal processes. Also note the domination of black coloured heavy minerals; (d) Proliferation of commercial and construction activities up to the hitherto intertidal zone, perhaps extended into the sea by “reclamation” efforts; (e) The search for tropical beach for recreational –leisure activity, has in effect, dwindled the beach; (f) Wave cut terrace along the Kovalam region; (g) The coastal swamps and mires associated with backwater ecosystem, are under enhanced levels of nutrient influx and are being deteriorated; (h) Riprap wall being constructed, rather unsuccessfully to protect the seaward migration of anthropogenic constructions; (i) The unintended cause of ripraps: active loci of pollutants and their retention.

5 Discussion

5.1 Depositional environments and processes

While tourism is often explored from a broad sociocultural perspective, several empirical studies have also focused on the impact of physical characteristics and depositional dynamics in the beach environments along the Indian coastline. A sedimentological study on the tourist beaches of Chennai (Santhiya et al., 2016) employed granulometric analysis, Linear Discriminant Functions (LDF), C–M plots and heavy mineral analysis to understand sediment deposition and transport. Similarly, a seasonal analysis of sediments along the Kalpakkam-Mahabalipuram coastal stretch (Deepthi et al., 2018) demonstrated the influence of both marine and terrestrial inputs. The sampling was conducted during different monsoonal periods to assess the temporal variations and collected along a transect. In another detailed investigation, the Chandrabhaga beach sediments were examined to reconstruct the paleodepositional environment (Mishra et al., 2024). In relation to the formation processes of mudbanks along the Kerala coastline in India, detailed surveys of the nearshore bathymetry and sediment characterization were conducted by Narayana et al. (2008). It included the textural and geotechnical characteristics of the surface sediments of a mudbank were analysed during the pre-monsoon, monsoon, and post-monsoon seasons. Narayana et al. (2008) concluded that with the same modal grain size, the monsoon seabed had a texture comparable to that of the pre-monsoon seabed; however, the amount of coarse silt and sand increased nearshore, while the amount of fine and very fine silt increased offshore. During the monsoon season, the seaward-fining textural gradient became more noticeable. Especially, the high river discharge during the monsoon season may have facilitated the transport of trace metal rich sediments to the lower reaches of central Kerala (Babu et al., 2023). The wave regime along the entire Kerala coast is primarily influenced by meteorological conditions in the Arabian Sea and the Indian Ocean, with peak wave activity occurring during the monsoon (Kurian et al., 2009). The beach is a dynamic environment that is usually affected by the long shore currents, waves, fluvial inputs, offshore currents, and winds (Edwards, 2001). This dynamism invariably influences the textural properties of sediments being transported or deposited in the beach/coastal environment. The presence of moderately well sorted and moderately-sorted sediments indicates the influence of strong energy conditions in the area (Chauhan, 2014). From the granulometric data it is inferred that the samples from Hawa and Chowara beach respectively consist of fine sand and medium sand with moderately well sorted to moderately sorted, fine skewed to coarse skewed characteristics. Irrespective of the season, positive skewness dominates in beach sediments revealing unidirectional transport or the deposition of sediments in sheltered low energy environment (Brambati, 1969; Deepthi et al., 2018). The Lighthouse and Pozhikkara samples range from very fine sand to pebble with well sorted nature in Lighthouse and extremely poorly sorted to moderately well sorted in Pozhikkara and represent strongly fine skewed to strongly coarse skewed nature. The Chowara sediments are characterised by moderately well sorted, medium sands and fine-nearly symmetrical skewed and are very leptokurtic to platykurtic, while the other locations are dominated by fine sands that are extremely poorly sorted to moderately sorted characteristics. The occurrence of graded suspension in this study is attributed to the significant influence of relict sediments (e.g., Krishnakumar et al., 2011). These samples experienced rolling and suspension, suspension with rolling and graded suspension modes of transport. Together, these traits indicate and or affirm the interpretation of influx of sediments from north and their southerly transport, progressive increase in sorting and prevalence of higher energy conditions at Chowara wherein fines are specifically winnowed away.

Beaches are quickly adapted to fluctuations in wave and tide conditions by shifting their sediments through oscillatory and quasi-steady currents, leading to patterns of spatial erosion (sediment divergence) and accretion (sediment convergence). The discriminant diagrams (Fig. 2a and b) shows that majority of the samples fall under river field, except for samples from Chowara, which fall in the beach field. Additionally, in both diagrams, the samples from Pozhikkara plot far from the discriminant lines while the Hawa and Lighthouse samples are near the discriminant line and the Chowara samples within the beach field. This distribution may be attributed to sediment transport from land to sea through coastal erosion, a process specifically influenced by waves and currents activity, which reworks and redistributes material along the shore as reported by Holland and Elmore (2008). In a first approximation, this phenomenon can be construed as influx of sediments from north and or supply of major fluvial sediment in the north and gradual littoral transport along the shoreline/beach, during which the fluvial sediments gradually gain the marine signature could be interpreted. Whether complementary or contrary to this inference, the presence of a significant volume of sediment that remains unincorporated into marine sediments suggests a disparity between the operational rates of fluvial and marine processes in imprinting their respective signature on coastal/beach sediments. The bivariate plot of Mean size (Mz) vs Standard deviation (SD) (after Glaister and Nelson, 1974) that differentiates the relative maturity of the sediments within a range from source-sink, i.e., alluvial fan to mature beach, shows all the samples away-far away and farthest from the mature beach field (Fig. 2c). In this context, the samples other than Chowara fall in close proximity and the samples of Chowara show a wide disparity from alluvial fan to good sorting, affirming the prevalence of disparity among Chowara and other samples may reinforce the interpretation of northerly introduction of sediments into the beach that gradually acquire marine signature during southerly littoral transport. Furthermore, the absence of any samples from the mature beach supports the earlier inference of excessive sediment input from fluvial sources and the lack of marine imprinting on the sediments transported into the marine environment. Lighthouse and Hawa are pocket beaches which are dynamically stable with nearly consistent seasonal erosion and accretion. These variations are in tune with the rough and fair-weather seasons in which, during the erosion, light mineral grains are carried out from pocket beaches and rest of the heavy mineral remain unaffected.

The Pozhikkara beach recorded high erosion and those eroded material from beach and sediment from KKB are carried by fluvial process are the main source for sediment to the beach (Sajinkumar et al., 2017; Sathish et al., 2023). This is supported by discriminant diagram that shows samples of Pozhikkara beach falling both in the fields of fluvial and wave process. The Chowara samples are not in accordance with any of the processes and fall into partially river and marine field, according to the discriminant diagram (Fig. 2d; Stewart Jr., 1958), which separates the samples according to their relative energy conditions of deposition as well as unidirectional, bidirectional, and no motion categories. This helps identifying the predominance of fluvial, marine and quiet water environmental settings. Though there is certain difference of preservation of fluvial signature and acquiring of marine are indicated with reference to the locations which in turn is slightly different from the inferences based on previous diagrams, prevalence of disparity between samples of Chowara and other locations, transience of sediment samples from fluvial-marine signature, and complete absence of quite water environmental setting are all indicated. Though all the studied samples fall above the C=M divide, uniqueness of the samples of Chowara are also indicated by the discriminant diagram of prevalent transport mode. These samples fall as an isolated cluster than other samples and experienced more of rolling mode of transport (Fig. 2e). This phenomenon is extremely opposite to central part of Kerala where sediment drifted toward the north direction by northern oceanic current. The movement of sediment along the shoreline might have been associated with seasonal oceanic currents. The headland lies between Hawa beach in the north and Chowara beach in the south and the outcrops plays a significant role in controlling the hydrodynamic factors (Chenthamil Selvan et al., 2020). Those cliff act as barrier to blockage of the sediments from either side might be resulting in the high accretion in the Chowara beach (Arunkumar and Joseph, 2015; Chenthamil Selvan et al., 2020).

Plotting the granulometric data in bivariate diagrams of SK vs Mz, SD vs SK and Mz vs SD affiliate all the studied samples into fluviatile in origin and within which the geographic variability of Chowara and Hawa could be observed. Together, continental fluvial source for the sediments that occur in all the beaches, relatively higher rates of sediment influx than the marine agents could imprint their signatures on them and also relative absence of shoreward sediment transport from offshore could be discerned (Fig. 4a). Selvaraj and Mohan (2003) also noted the sediments from beaches were deposited from river, dune and beach environments. The samples falls in the field of river channels and overbank deposits, clustered together except the Chowara and Pozhikkara (Fig. 3f) but only sample from Pozhikkara falls to the extremity as shown in Fig. 3g. In addition, the LDF diagrams indicates that most of the samples are in the field of beach environment/deposition while, the P1 and P2 samples are fluvial in origin. This suggests that present day beach sediments were initially deposited in a shallow marine setting, with subsequent marine regression shaping the current shoreline (Angusamy and Rajamanickam, 2007). Additionally aeolian processes have also influenced sediment transport in the study area. Among the four study sites, Pozhikkara, the northernmost beach, is situated at the confluence of the Killi River and is surrounded by numerous tourists resorts (Ramkumar et al., 2023). More than 90% of the samples are deposited by turbidity currents except P1 and P3. Thus, on the basis of textural analysis, it can be concluded that though the sediments were primarily riverine in origin, these have been reworked by sea waves into beach sands with some aeolian influence. Though beach environments experience stronger wind, the growing influences of aeolian influence could not be ruled out as a result of removal of natural vegetal cover, however, the relative contribution of which is not yet ascertained affirmatively.

5.2 Influence of natural and anthropogenic processes/mechanisms

Coastal engineering projects, such as seawalls, groynes, and jetties, are designed to protect coastlines from erosion and flooding (Angnuureng et al., 2023). However, these structures can also alter sediment transport dynamics, potentially exacerbating erosion in adjacent regions (Anthony, 2013). Urban development and infrastructure projects in the study region disrupt natural sediment transport patterns. The interplay between natural and anthropogenic drivers of coastal morphology changes is complex and often nonlinear (Chowdhury et al., 2023). Understanding these processes is essential for effective coastal management and mitigating the impacts of climate change and human activities. Similarly coastal erosion results from both natural processes, such as sea level rise and storms (Boudet et al., 2017) and human activities, including embankment and seawall construction, port development, sand excavation, and boulder placement (Jana and Bhattacharya, 2013). These factors disrupt coastal fluid dynamics and sediment dispersal pattern, impacting both short-term and long-term coastal stability. Boyall et al. (2023, 2024) investigated how variations in natural climate, environment changes, as well as human induced landuse modification influence sediment deposition and preservation. Deforestation around the lake and broader landuse modifications in the catchment would reduce soil stability, leading to increased erosion and sediment deposition in the lake, accelerating its infilling (Boyall et al., 2024). Similarly, the enhanced sediment load from terrestrial sources can impact coastal dynamics. Eroded materials transported by river systems contribute to coastal sedimentation altering grain composition by introducing finer, land-derived sediments into marine environment. This process can influence shoreline stability and sedimentary deposition patterns over time. The erosion of beaches along India's west coast are primarily influenced by factors such as the slow rate of sediment discharge by rivers, groyne construction, groyne spacing and length, longshore currents, and the preferential northward transport of sediments (Pradeep et al., 2022). Coastal erosion is a significant issue in Thiruvananthapuram District, affecting approximately 23% of its coastline (https://www.irrigation.kerala.gov.in/coastal-map-tvm). The district's coastline is highly vulnerable to erosion due to high and rogue waves, and seasonal storm surges. This erosion has led to the loss of land, property, and livelihoods, particularly impacting the coastal tourism.

The global supply of detrital sediment to the sea mainly comes from terrains due to denudation of land by rivers, glaciers, and aeolian processes. Once these reach the marine realm, depending on the vagaries of multiple oceanographic processes they acquire marine signatures depending on the rates of sediment supply, reworking, coastal transport and redistribution before final burial. The duration between which the sediments were deposited and buried also crucial for retaining the provenance signatures and or imprinting different percentages of marine signatures. Although Pozhikkara sediments have a riverine origin, certain riverine and marine characteristics that can be explained by the influence of Killi River. The occurrence of riverine characteristics, along with rolling-suspension modes of transport in the southern beaches are likely reflects the influence of anthropogenic activities in the beach and subtidal regions. These activities may led to sediment resuspension and disrupt the natural tidal, littoral current, and wave-driven processes that are responsible for selective sorting and winnowing. Aggravation of selective removal of fine/light sediments and due to which enhanced deposition of heavy mineral layers also been witnessed in almost all the beaches (Figs. 5 and 6). Superimposed on these are the occurrences of aeolian characteristics of the beach sediments. While dry beaches may encourage formation of isolated dunes and admixture of aeolian sediments in the beach/littoral sediments, location of rainforest region and experiencing of tropical moist-wet conditions in major part of the year in the studied region do not correlate well. It may be due to enforced drying of coastal stretches, exposing the tidal flat and former berm-beach ridge-swale complexes into dry stretches due to landcover change (Fig. 5), the loss of natural protective covers such as *Ipomoea bioloba* and other beach vegetation may also be a reason for enhanced beach erosion by aeolian activity and the contribution of aeolian sediments to the beach-littoral sedimentary records. All the samples are within the aeolian/beach environment (Fig. 4b) while Chowara samples extend towards beach/shallow environment from littoral environment. The construction of seawalls, riprap revetments, and groynes has been implemented to mitigate the effects of erosion, but these artificial structures are also subject to erosion. The protected beaches also undergo augmented erosion (Fig. 6) and the rip-rap boulders provide niche for pollutant accumulation. Efforts to manage and reduce coastal erosion are ongoing, but the challenges remain substantial. Though this study it is inferred that the sediments of selected beaches are highly disturbed due to its grain size shows from coarse to fine which is well sorted to poorly sorted suggesting active transport and reworking, multiple sediment sources, and varying energy conditions. The differences in kurtosis from very platykurtic, mesokurtic to extremely leptokurtic indicates high energy of deposition. Most of the samples are very fine to fine, some few other having coarse to nearly symmetrical skewness signifying highly disturbed nature of the sediment and by implication, substrate characteristics, on which many micro-meso-macrobenthics depend for their livelihood. It signifies that the alterations in sediment characteristics by anthropogenic activities, especially tourism have not only directly altered the sediment textural properties, but indirectly the substrate characteristics as well, an important ecosystem trait, many a coastal living organisms depend on.

5.3 Global comparison and implication of the results

The tropical sandy beaches of the west coast of India are a crucial ecosystem. These beaches support the tourism-based local economy, are highly threatened and considered as one of the most contaminated sedimentary environments due to wide range of anthropogenic and recreational activities. The tourism activities contribute to coastal environment degradation, erosion, and pollution to a greater extent (Ramkumar et al., 2023; Da Costa, 2024; Pradhan et al., 2024). Our textural analysis of sediments from Kovalam sandy beach indicates a severe degradation of coastal environment as most samples are very coarse, moderately well sorted, coarse to fine skewed and platykurtic in nature with majority of the samples falling within the river field. These findings align with similar studies such as Pradhan et al. (2024) on the Chennai coast, Mohanty et al. (2021) on the East coast of Odisha, Buynevich and FitzGerald (2003) on the Maine coast, USA, Deepthi et al. (2018) on the Kalpakkam coast, and Alharbi et al. (2016) on the Red sea coast which reported sediments ranging from coarse to medium sand, moderately well sorted, coarse to very fine skewness with Platykurtic to leptokurtic characteristics. Comparable findings have also been observed by Mohammad et al. (2020) in Visakhapatnam coast, Pradhan et al. (2020) along tourist beaches of eastern India, Rizzetto (2022) on the East Venetian coast, Mohtar et al. (2017) on the Batu Pahat coast, and Vasudevan et al. (2024) in Kerala coast-highlighting sediments ranging from medium to fine sand, very well to moderate sorting, very coarse to very fine skewness, and Platykurtic to very leptokurtic properties. However, contrasting findings were reported by Nugroho and Putra (2018) in Waikelo beach, Rashedi and Siad (2016) on the Abu Dhabi coast, Hegde et al. (2021) on the central west coast of India, and De Luna et al. (2024) on Baretta beach, where sediment characteristics ranged from coarse to fine sand, well sorted to very poorly sorted, very coarse to very fine skewness with platykurtic to very leptokurtic nature.

The comparison of the textural characteristics of the Kovalam beach with global counterparts suggests that its natural morphology has been significantly altered due to overexploitation of coastal zone, tourism development and beach farming. This has led to elevated urbanization along the coastal stretch over the last few decades (Dessai, 2023; Nagarajan et al., 2023; Ramkumar et al., 2023; Rizetto et al., 2025; Zhang et al., 2025; Zhou et al., 2025). Tourism-related infrastructure development such as road widening and sand mining, has resulted in a sediment deficit, degradation of foredune, and coastal erosion (Thinh et al., 2019; Alcántara-Carrió and Cabrera, 2002; Yuvaraj et al., 2023, 2024; Dulias, 2024). Furthermore, the construction of engineering structures along the Kovalam beach has modified the sedimentary dynamics, disrupted sediment sources, and disturbed the balance between erosion and deposition resulting in the landward migration of shoreline (Li et al., 2018; De Paula et al., 2021; He and Shuai, 2021; Buzzi et al., 2022; El-Masry, 2022; Zhang et al., 2025). Tropical sandy beaches are increasingly impacted by stressors that operate across a wide range of temporal and spatial scales from short term local, disturbances such as trampling, to long term, global challenges such as climate change (Santos et al., 2019; Costa and Zalmon, 2019a,b; Fanini et al., 2020). This study analyses and documents the sediment dynamics of Kovalam coast through detailed textural analysis, indicating the disruption of balance in the intertidal region along with landuse/landcover changes to assess habitability and sustainability, implying the utmost need of remedial measures.

6 Conclusions

The beach sediments were likely deposited in a shallow marine beach environment in agitated water, with contribution from aeolian source through suspension and rolling as the deposition mechanisms. Initially these sediments were originated as river channel deposits before undergoing reworking to their present location. Development of concrete structures and conversion of natural landcover as a direct result of growing recreational activity in the beaches have provided impetus for exponential transformation of sediment textural characteristics, burial rates, transport modes and substrate characteristics as documented in the present study. Imprinting of aeolian characteristics, partial retention of fluvial characteristics and prolonged duration of imprinting of marine signature on the sediments introduced into the marine realm have also been documented. Together, it can be concluded that while the coastal tourism in the studied beaches has been firmly entrenched, the associated repercussions on sediment texture, substrate characteristics, types and quantum of sediments that get preserved in the coastal sedimentary record have also taken an irreversible negative trend. Efforts to contain coastal erosion, drying of coastal patches and waste management have to be site and measure specific for getting tangible, sustainable results and habitability.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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