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Spatio-temporal variability of macrobenthic fauna at Sandy Beach Clifton, Karachi, Pakistan

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Abstract

Sandy beaches are home to a diverse array of macrobenthic communities that serve as important indicators of ecological health. This study examined the spatiotemporal variability in macrobenthic assemblages along the sandy beach of Clifton, considering environmental factors such as temperature, salinity, dissolved oxygen, and the monsoon season. A total of 10 sites, covering an approximate sea area of 10 km (Clifton, Karachi coast, Pakistan), were sampled monthly from January to October 2024 to understand the community structure of macrobenthic communities and their relationships under ecological and environmental factors. Ten species of macrobenthic assemblage, eight molluscans, four bivalves and four gastropods, and two crustaceans were identified. *Balanus trigonus* (mean 188.3 ± 72.5) and *Babylonia spirata* (127.1 ± 54.6), the two most prevalent species, achieved their maximum abundance in June (mid monsoon, 198 individuals) and March (early monsoon, 297 individuals), respectively. The study of the marine species abundance data using the Generalized Additive Model (GAM) revealed faint, non-linear seasonal trends, enhancing and expanding on the patterns. Plankton blooms and favourable breeding conditions coincide with the warmer

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months of March through August, when *Balanus trigonus* and *Babylonia spirata* exhibit observable peaks. The GAM emphasizes the ecological differences among Anadara species: While *A. indica* exhibits a low-abundance, flat curve, suggesting either competitive exclusion or niche divergence, *A. inequivalvis* shows a robust summer peak. Stable species, such as *Neverita didyma*, exhibited near-linear patterns, indicating low seasonal susceptibility. A noteworthy late-season surge in *Portunus sanguinolentus* could be the consequence of a reproductive strategy or predator-prey dynamic. Effective Degrees of Freedom (EDF) showed that temperature, salinity, DO, and macrobenthic community structure were all substantially correlated. Furthermore, long-term monitoring is required on the sandy shore of Clifton, a crucial habitat for macrobenthic communities.

Keywords: Community structure; Environmental variables; Monsoon; Sandy beach; Molluscs; Crustaceans.

1. Introduction

Oceans frequently develop a front region between the bottom and surface near the continental shelf break owing to variations in the characteristics of the water above and below this area (Azad and Mehrfar, 2017). Sandy beaches are crucial socio-ecological systems for both coastal stability and human well-being. They are also valuable cultural and economic resources, but their biodiversity and ecosystem services are threatened by urbanization (Augusto *et al*., 2025). The Global Assessment also warns that observational evidence suggests the impacts of biodiversity shifts are already being felt in fisheries, aquaculture, agriculture, and the benefits that nature provides to humans, and that these consequences could worsen and become more acute (Muller-Karger *et al*., 2025).

Sandy beaches cover approximately 75% of the world's coastline and have longer intertidal systems with a more dynamic environment (Bascom, 1980; Lercari and Defeo, 2003). The intertidal zone, which lies between the low- and high-water marks, is a narrow band at the interface of land and sea. It experiences extreme environmental gradients due to tides and waves, resulting in significant fluctuations in moisture and temperature between high and low tide periods. Physical and biological factors, as well as man-made and natural causes including beach morphodynamics, erosion, and subsidence, determine the macrofauna community structure (Bozzeda *et al*., 2025). Studying coastal dynamics and littoral geomorphological processes involves various analyses, including assessing key sand size parameters such as median grain size (D50) (Lopez-Garcia *et al*., 2021). The macrobenthic fauna may be numerous in medium and fine sands, but the macrobenthic density per unit area is typically higher in organically rich fine compact sediments. Grain size and mud content of the sediment are two physical parameters that affect the structure of the benthic fauna at sandy beaches.

(Van Hoey *et al*., 2004). The existence of organic detritus and substrate stability is associated with an increase in macrobenthic variety and abundance (Jenderedjian *et al*., 2007).

The texture of the sediment and the benthic communities are impacted by natural large-scale physical disturbances such as weather, tides, waves, and currents (Arshad and Farooq, 2018). Environmental disturbances can be effectively mitigated by macrobenthos, which are also considered as an efficient indicator of pollution (Frontalini *et al*., 2011). Temperature, sediment wetness, and the duration of air exposure are all important variables in the intertidal zones of macrotidal beaches, determining the macrofauna's spatial distribution (Aviz *et al*., 2025).

Pakistan has diverse and abundant marine life, encompassing estuaries in coastal areas and open ocean waters (Arshad and Farooq, 2018). Climate models predict an increase in oceanic temperatures, substantial changes in oceanic heterogeneity, flow patterns, and convective overturning, ultimately affecting light availability at the sea surface. These alterations are expected to cause significant losses and changes in marine ecosystems. Given the alarming rates of species extinction, urgent actions are required to conduct biodiversity assessments and determine the global species count (Borja *et al*., 2016). Rafique and Shah (2019) have documented that the beach's popularity has resulted in environmental concerns for both human visitors and marine species. The coastline of Pakistan also experiences with monsoon season every year, which influences macrobenthic communities.

Clifton Beach has numerous nursery grounds for various bivalves, gastropods, decapods, and polychaetes. Anthropogenic activities like beach driving, fishing, and sewage water drainage frequently damage this beach. (Arshad and Farooq, 2018). To establish a correlation between the macrobenthic community structure and the monsoon season, along with physicochemical factors, studies are required for the management of Clifton Beach as well as the macrobenthic community.

This study's objectives are to examine how macrobenthic assemblages at Clifton Beach are affected by phytochemical factors and the monsoon season, and disruptions of the macrobenthic community. The current investigation evaluates both the effects of monsoon and physicochemical parameters on the macrobenthic community.

2. Materials and methods

Karachi, the largest city in Pakistan, serves as the country's population and business capital. It is located approximately 130 km west of the Indus estuary and situated on the northern coast of the Arabian Sea. Karachi, including its suburbs, occupies more than 3530 km² and has an estimated population of 18 million (Feroz and Hadi, 2016). The densely populated city of Karachi boasts a population of 18,076,800. (Karachi Population, 2025).

2.1. Area of study

The coastal belt along the Karachi Coast spans approximately 100 km and is located between the Gharo Creek and the Hub River to the west (Ali and Dinshaw, 2016). The sea view beach was studied along the coastal belt of Karachi Coast as shown in Figure 1.

One of Karachi's most popular seaside destinations is Clifton Beach, also called Sea View, which is located close to 10 km of shoreline (Kausar *et al.*, 2025). The designated area is a popular marine tourist destination, offering a range of recreational activities. The beach sands exhibit a tan to brown coloration, contain abundant mica particles, and are characterized by the presence of ample silt (Tirmizi *et al.*, 2012).

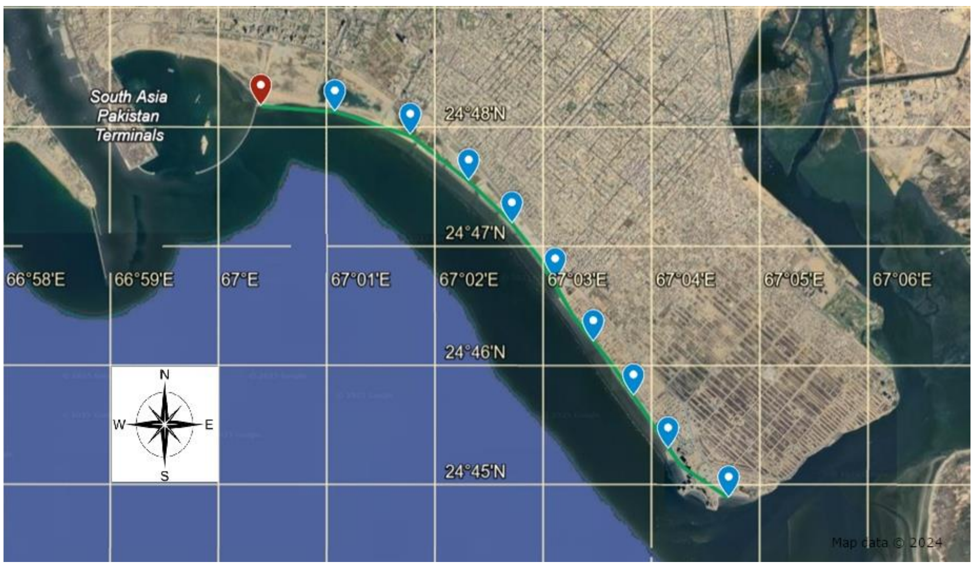

Figure 1. Map indicating the study area of Clifton Beach at Karachi's Coast (Map Source: Google Earth, 2024)

2.2. Sampling and census

Ten equally spaced intertidal shore stations were sampled along replicated transects on each site. Sampling was conducted based on tidal charts, focusing on sub-littoral zones exposed during low tides, with tidal heights ranging from -0.02 m to 1.2 m. A total of 10 stations, spaced 1 km apart, were selected for sample collection (Figure 2). Quadrats, measuring 1 × 1 meters, were established at each station.

The quadrats at each site were measured as 1×1 meters. The sites selected to conduct the species count were divided into ten. At each site, four quadrats were used to count the species (250 meters apart). The line transect method was used to calculate the abundance of fauna other than the invertebrates.

During low tide, these animals can be found near the -0.03 m tide height, making it an important feeding ground. During the field study, samples were collected and preserved. The samples collected were washed in seawater and sieved through one-millimeter mesh and were preserved in 70% alcohol (mollusk and crustaceans) and 4% formalin in glass jars (annelids) for detailed laboratory analyses of the collected animals. Grain size analysis, temperature, pH, salinity, and dissolved oxygen levels were analyzed (Hanna instrument Italy: Model: HI2003, MColortest HC559538, thermometer) to establish correlations and serve as fundamental data for predicting future climate change activities. Monthly and seasonal fluctuations in sea temperature were recorded and assessed to determine water salinity. Salinity measurements were taken using a salinometer, both on-site and in the laboratory. Sediment samples were collected using a yabby pump to a depth of 2 ft and sieves (Lastra *et al*., 2006).

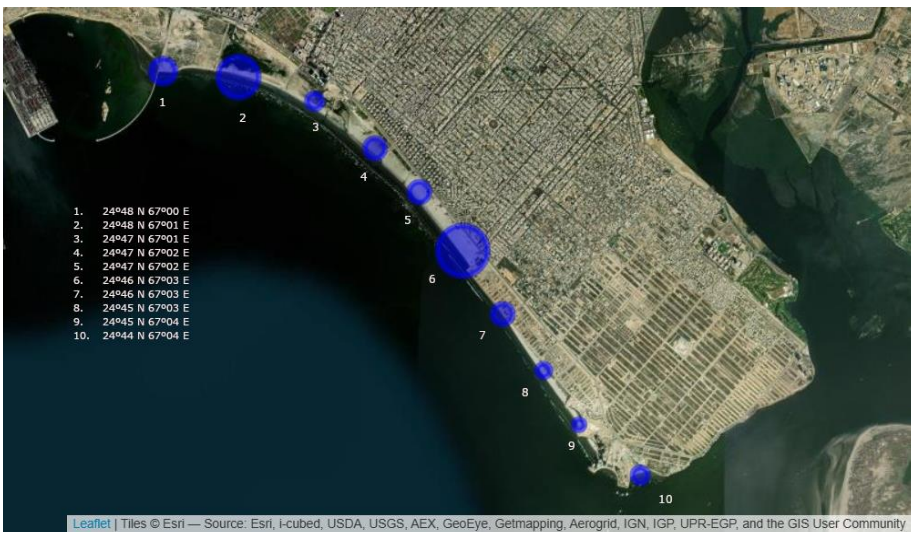

Figure 2. Map showing the abundance of species from the study areas (Map Source: Map data ©2025 Esri, Maxar, Earthstar Geographics, and the GIS User Community)

2.3. Indices

This study examined the structure of marine communities using several important ecological diversity measures. Overall species diversity was measured using Shannon's Diversity Index (H'), which included species richness and evenness using the proportional abundance (pi) of each species (Shannon and Weiner, 1963). Pielou's Evenness Index (J), which ranged from 0 (uneven) to 1 (perfect evenness), assessed how evenly individuals were distributed among species, whereas Margalef's Index (R) (Margalef, 1957) provided a measure of species richness irrespective of sample size (Pielou, 1967). When combined, these indices allowed for a thorough assessment of the temporal and geographical variance in megafauna populations, providing information about resource partitioning (Pielou, 1967), taxonomic breadth (Margalef, 1957), dominance hierarchies (Simpson, 1949), and rarity (Shannon, 1963) in the research area. By addressing potential biases in single-index techniques, the combined use of these measures ensured robust characterization of community dynamics.

2.4. Statistical analysis

This study used Generalized Additive Models (GAMs) to examine the effects of salinity, temperature, and dissolved oxygen on marine species abundance. GAMs were selected over conventional linear models because they can capture threshold effects and non-linear interactions, which are prevalent in ecological systems where species frequently react to environmental gradients in complicated ways. For instance, GAMs permit curved responses, such as peaks or abrupt declines, which more accurately represent biological tolerances in the real world, whereas linear models presume a straight-line relationship between temperature and abundance. The Poisson distribution was used to illustrate the GAMs. (Cross *et al.*, 2024).

The special capacity of generalized additive models to handle the intricate, non-linear interactions frequently found in ecological systems led to their selection for this study. Instead of imposing strict, straight-line correlations, as standard linear models do, GAMs use adaptable smooth terms such as temperature that can adjust to the actual shape of species-environment relationships without the need for specified functional forms. Species reactions to environmental gradients frequently follow unimodal curves or threshold patterns (e.g., the sharp drop of oxygen-sensitive species below 4 mg/L DO), which makes this flexibility useful in ecology. Critical information about response complexity can be gleaned from the diagnostic outputs of the models, especially the Effective Degrees of Freedom (EDF). Low EDF values indicate generalists with wider tolerances, whereas high EDF values indicate specialist species with narrow optimum ranges. Additionally, GAMs produce outputs that are easy to understand, such as heatmaps and smooth curves, which clearly illustrate how species abundance changes along environmental gradients. GAMs are particularly well-suited to revealing the complex, frequently non-linear dynamics that control species distributions in marine ecosystems, where abrupt thresholds and optimal ranges are the norm rather than the exception, due to their combination of analytical strength and visual clarity. The ability of this approach to highlight key ecological trends without simplifying intricate relationships gives managers useful information for setting conservation priorities.

3. Results

3.1. Abundance

The Shannon-Weiner Index was 1.995. As variations were observed on the site, the index increased. The value of Simpson's Index (D) was 2.308, indicating the likelihood that arbitrarily nominated individuals belonged to the same group, as shown in Table 1. In contrast, Simpson's Index of Diversity (1-D) was determined to be 1.308, indicating that randomly chosen individuals would fit dissimilar categories. Furthermore, the Simpson's Reciprocal Index (1/D) yielded a value of 0.764, indicating the number of equally common species that contributed to the observed Simpson's Index. Margalef's index was 1.50, and Pielou's Index was 0.866 (Table1).

Table 1. Calculations conducted to identify different diversity indices

Metric	Formula	Values
Total Number of individuals	N	5257
Shannon-Weiner Diversity	$H' = - \sum pi \ln (pi)$	1.995
Simpson Index	$D = sum (pi^2)$	2.308
Margalef's Index	$M= (S-1)/ \ln (N)$	1.50
Pielou's Index	$E=H/ \ln (S)$	0.866

Regarding the computation of physicochemical parameters, the temperature readings at all ten stations ranged between 22 and 30 °C. Eight families of molluscs were identified based on the findings of the research, of which four families were bivalves of four species: *Anadara inequivalvus* (Bruguière, 1789), *Anadara indica* (Gmelin, 1791), *Anadara natalensis* (Krauss, 1848), *Mactra antiquate* (Spengler, 1802), and four belonged to gastropod families: *Babylonia spirata* (Linnaeus, 1758), *Ergaea walshi* (Reeve, 1859), *Ranella olearium* (Linnaeus, 1758), *Neverita didyma* (Röding, 1798), and two families of arthropods Balanidae in which one species of *Balanus trigonus* (Darwin, 1854) and one species of *Portunus sanguinolentus* (Herbst, 1783) of Portunidae were also identified.

The optimal temperature range for mollusc assemblages is between 24 and 30 °C. *Babylonia spirata*, the most abundant species, exhibited peak responses to temperature, salinity, and dissolved oxygen. The optimal temperature for *Babylonia spirata* is between the temperature ranges 24-26 °C in March and April (pre- and early monsoon period) with optimal salinity 35‰, and 7.5-4.5 mg/L dissolved oxygen. *Babylonia spirata* avoids high salinity (40‰). *Anadara inequivalvus* abundance was reported in March (pre-monsoon) with salinity 32‰, showing strong salinity dependence but no temperature response. *Balanus trigonus* is considered a temperature-independent species, with no effect of temperature on its abundance. *Portunus sanguinolentus* responded only against temperature, showing peak abundance at 24°C in March (pre-monsoon) and is considered as temperature specialized species.

3.2. Temporal variation

When applied to marine species abundance data, the GAM analysis shows subtle, non-linear seasonal trends that complement and build upon the patterns. The complex and frequently irregular reactions of species to seasonal environmental changes are captured by GAM, which models monthly abundance using smooth functions. The hump-shaped GAM curves of major filter feeders, such as *Balanus trigonus* and *Babylonia spirata,* show noticeable peaks during the warmer months (March–August), which correspond to plankton blooms and ideal breeding conditions. Their dramatic fall reductions (September–October), on the other hand, are represented as steep downhill slopes and are probably related to changes in salinity or food availability brought on by the monsoon. Ecological differentiation between Anadara species is also highlighted by the GAM: *A. inequivalvis* exhibits a strong summer peak, but *A. indica's* low-abundance, flat curve points to either niche divergence or competitive exclusion. Near-linear trends are exhibited by stable species, such as *Neverita didyma*, suggesting low seasonal sensitivity. GAM shows a notable late-season spike in *Portunus sanguinolentus*, which defies the overall decline and may be the result of a predator-prey dynamic or reproductive strategy (Figure 3).

These findings highlight how well GAMs can separate seasonal causes from species interactions, giving theories regarding competition, environmental stresses, and conservation priorities a statistical basis. These findings could be improved and the causal mechanisms underlying the observed abundance patterns clarified by further integrating abiotic factors such as temperature, into the GAM framework.

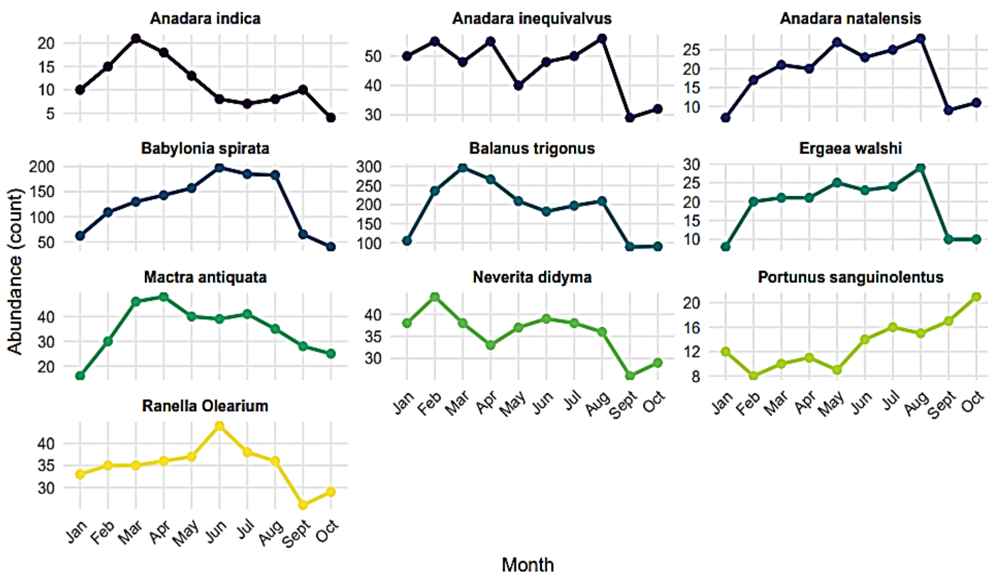

Figure 3. Temporal variation of species observed across all sites

Table 2 shows distinct trends in marine organism abundance over ten months, both by species and by season. *Balanus trigonus* (mean 188.3 ± 72.5) and *Babylonia spirata* (127.1 ± 54.6), the two most common species, achieved their maximum abundance and controlled the ecosystem in March (297 individuals) and June (198 individuals), respectively. These large numbers are probably due to good conditions like warmer temperatures, more plankton being available, or reproductive cycles that happen in the summer (March to August). However, *Anadara indica* (mean 11.4 ± 5.0) and *Portunus sanguinolentus* (13.3 ± 4.0) had the lowest abundances, with *A. indica* being especially rare in October (four individuals). *Anadara inequivalvis* is the most common species, with a peak of 56 individuals in August (46.3 ± 9.2).

In contrast, *A. natalensis* (18.8 ± 7.1), and *A. indica* have lower and more variable numbers. With *A. inequivalvis* more suited to local conditions, this implies potential niche partitioning or competitive exclusion. From September to October, the majority of species see a noticeable drop in abundance, which could be brought on by post-spawning mortality, the seasonal effects of the monsoon, or a diminished food supply. Stable populations, such as *Neverita didyma* (34.2 ± 5.4) and *Ranella olearium* (34.9 ± 5.3), exhibit less seasonal reliance, whereas species with high population variability (e.g., Balanus and Babylonia) may be more susceptible to environmental changes. *Portunus sanguinolentus* gradually increased from February to October, which may signify a late-season breeding cycle or a change in the dynamics of predator-prey relationships. With climate, food availability, and species interactions driving observed abundance patterns. The results generally demonstrate how biotic and abiotic factors interact to shape community structure and whether competition, predation, or environmental factors account for the low population of species.

Table 2. Mean monthly and species-wise abundance of marine organisms recorded

Species	Mean Abundance (±SD)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct
Anadara inequivalvus	46.3 ± 9.2	50	55	48	55	40	48	50	56	29	32
Babylonia spirata	127.1 ± 54.6	62	109	130	143	157	198	185	183	65	40
Anadara natalensis	18.8 ± 7.1	7	17	21	20	27	23	25	28	9	11
Ranella Olearium	34.9 ± 5.3	33	35	35	36	37	44	38	36	26	29
Mactra antiquata	30.8 ± 10.1	16	30	46	48	40	39	41	35	28	25
Balanus trigonus	188.3 ± 72.5	105	236	297	266	209	182	197	209	89	90
Neverita didyma	34.2 ± 5.4	38	44	38	33	37	39	38	36	26	29
Portunus sanguinolentus	13.3 ± 4.0	12	8	10	11	9	14	16	15	17	21
Anadara indica	11.4 ± 5.0	10	15	21	18	13	8	7	8	10	4
Ergaea walshi	17.7 ± 7.2	8	20	21	21	25	23	24	29	10	10
Monthly Mean (±SD)	52.3 ± 69.4	34.1	56.9	71.7	70.7	59.4	61.8	62	63.5	30.9	29.1

3.3. Environmental factors influencing the occurrence of species

The results of Generalized Additive Models examining the responses of intertidal species to three important environmental factors—temperature, salinity, and dissolved oxygen—are shown in Table 3. The findings show various species have different ecological strategies, with some taxa showing especially clear trends.

Extremely sensitive species have the strongest reactions. Due to its extremely significant non-linear responses to temperature (EDF=2.94, $p<0.001$) and salinity (EDF=2.52, $p=0.0006$), the barnacle *Balanus trigonus* has especially strong positive associations with all three environmental indicators. Similarly, the whelk *Babylonia spirata* shows considerable non-linearity in its salinity response (EDF=2.54), and it responds significantly positively to all parameters. These trends imply that these species serve as highly effective bioindicators of favourable environmental circumstances, with their abundance peaks probably representing ranges that are ideal for physiological function (Figure 4).

Table 3. Species response to environmental variables

Species	Predictor	EDF	p_value	Direction
Anadara inequivalvus	Temperature	1	0.0472	Positive
Anadara inequivalvus	Salinity	1.68	0.026	Positive
Anadara inequivalvus	Dissolved oxygen	1	0.0004	Positive
Babylonia spirata	Temperature	1.42	0.0046	Positive
Babylonia spirata	Salinity	2.54	0.0157	Positive
Babylonia spirata	Dissolved oxygen	1.95	0.0066	Positive
Anadara natalensis	Temperature	1	0	Positive
Anadara natalensis	Salinity	1	0.5636	No effect
Anadara natalensis	Dissolved oxygen	1	0.0018	Positive
Ranella olearium	Temperature	1	0.6984	No effect
Ranella olearium	Salinity	1	0.8289	No effect
Ranella olearium	Dissolved oxygen	1.45	0.2603	No effect
Mactra antiquata	Temperature	2.07	0.1039	No effect
Mactra antiquata	Salinity	1.6	0.5111	No effect
Mactra antiquata	Dissolved oxygen	1	0.2264	No effect
Balanus trigonus	Temperature	2.94	0	Positive
Balanus trigonus	Salinity	2.52	0.0006	Positive
Balanus trigonus	Dissolved oxygen	1	0	Positive
Neverita didyma	Temperature	1	0.5011	Slightly Positive
Neverita didyma	Salinity	1	0.182	Slightly Positive
Neverita didyma	Dissolved oxygen	1	0.0568	Slightly Positive
Portunus sanguinolentus	Temperature	1	0.7753	No effect

Portunus sanguinolentus	Salinity	1	0.9131	No effect
Portunus sanguinolentus	Dissolved oxygen	1	0.057	No effect
Anadara indica	Temperature	1	0.3303	No effect
Anadara indica	Salinity	1.21	0.279	No effect
Anadara indica	Dissolved oxygen	1	0.2934	No effect
Ergaea walshi	Temperature	1.85	0.0123	No Positive
Ergaea walshi	Salinity	1.30	0.0981	Positive
Ergaea walshi	Dissolved oxygen	1	0.0011	Positive

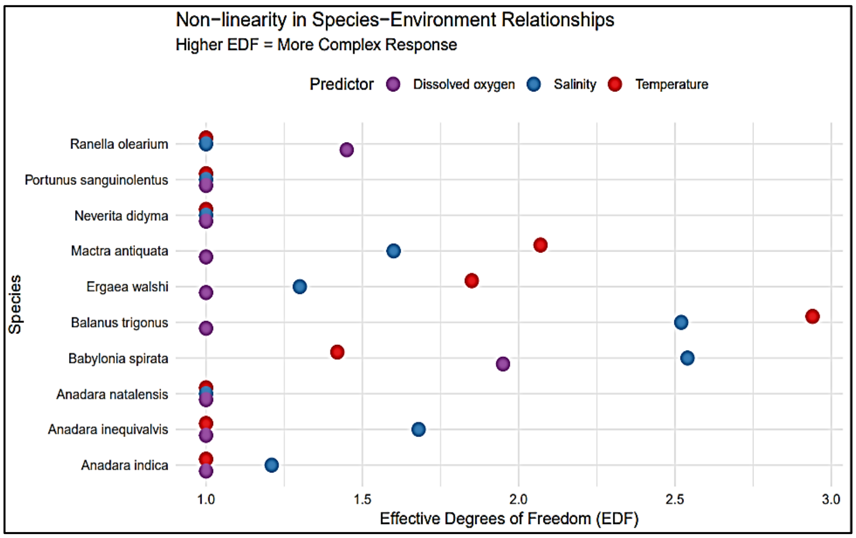

Figure 4. EDF (Effective Degrees of Freedom) Comparison

Species with moderate sensitivity show more selective reactions. *Anadara natalensis* only reacts to temperature and dissolved oxygen, whereas *Anadara inequivalvus* reacts favourably to all three factors. Among these closely related species, this variance within the same genus shows niche divergence. With no discernible salinity response, *Anadara natalensis* exhibits a temperature specialist pattern that suggests salinity tolerance but thermal adaptation. Species that are tolerant of their surroundings show few reactions. The crab *Portunus sanguinolentus* and triton shell *Ranella olearium* did not exhibit any significant correlations with any of the variables examined, indicating that they are either responsive to unmeasured influences or have wide tolerance ranges. Only slight positive trends are shown by the moon snail *Neverita didyma*, suggesting a poor environmental connection (Figure 4).

Some important ecological findings are revealed:

1. Non-linearity predominates: Most significant correlations have EDF>1, indicating ideal environmental ranges as opposed to straightforward linear responses.
2. Dissolved oxygen is important because it impacts more species (7/10) than salinity (4/10) or temperature (5/10) combined.

3. Variation at the genus level: Despite taxonomic similarities, Anadara species exhibit distinct reaction patterns.

The fact that different species have different levels of sensitivity indicates that the effects of climate change will be very species-specific, with tolerant species preserving ecosystem function and sensitive taxa like *B. trigonus* acting as early warning systems. When tolerance limitations are surpassed, minor environmental changes may cause sudden population shifts, as indicated by the occurrence of non-linear connections (Figure 4). The GAM analysis is used to identify the response of species to temperature, salinity, and dissolved oxygen fluctuations. In simple terms, we captured positive and negative relationships between abundance and environmental conditions (Figure 5).

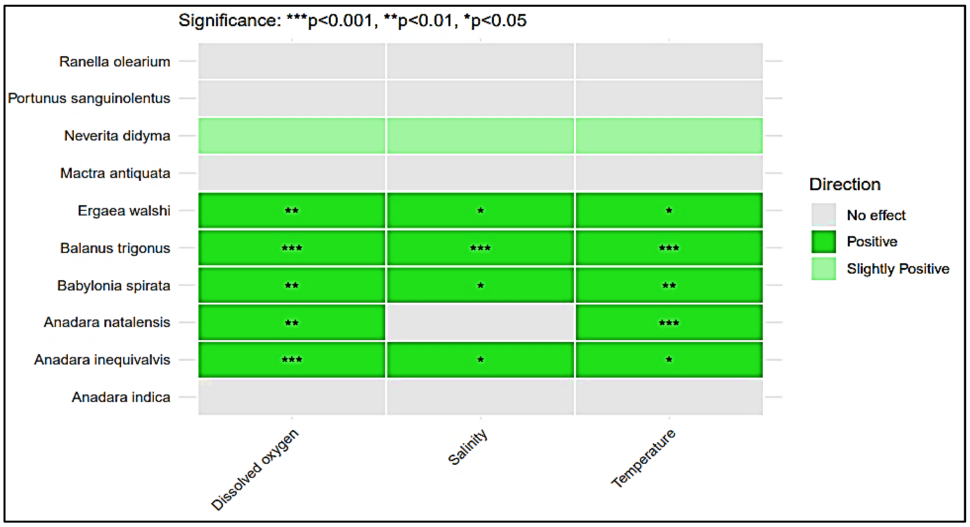

Figure 5. Direction Heatmap showing species responses to environmental predictors

In Figure 5, a clear visual summary of each species' responses to temperature, salinity, and dissolved oxygen is provided by the effect direction heatmap, which uses colour-coded tiles to show positive, slightly positive, or no significant effects. Grey tiles represent species like *Ranella olearium* and *Anadara indica* that do not significantly respond to these predictors, while green tiles highlight species like *Balanus trigonus* and *Ergaea walshi* that do well in environments with higher temperatures, salinities, and oxygen levels. *Ergaea walshi*'s strong positive reactions (indicated with stars) indicate that it is extremely sensitive to favourable conditions. Stars indicate statistical significance and aid in the identification of robust patterns. On the other hand, by measuring the linearity or non-linearity of these reactions, the EDF (Effective Degrees of Freedom) plot illustrates their complexity. Elevated EDF values (e.g., *Balanus trigonus* for temperature, EDF = 2.94) signify non-linear, peaked correlations, indicating that these species have ideal environmental ranges. Simpler, more universal responses are suggested by lower EDF values (e.g., *Neverita didyma* for dissolved oxygen, EDF ≈ 1). When combined, these plots show generalists with greater adaptability (low EDF + grey tiles) against specialists with limited tolerances (high EDF + green tiles), providing important information for forecasting ecological resilience in the face of environmental change. For example, *Ranella olearium's* flat responses imply a higher tolerance to variability, whereas *Ergaea walshi's* modest EDF and significant positive effects place it as a specialist susceptible to shifts outside of its optimal range. As a result, these visualizations are effective instruments for determining conservation priorities and projecting effects at the community level.

The findings of Figure 4 show three important ecological patterns:

1. Generalist vs. Specialist Approaches

   Species such as *Ergaea walshi* and *Balanus trigonus* have robust, non-linear responses (high EDF >2) to all predictors, indicating restricted optimum ranges. Their abundance drops outside of these thresholds and peaks at 27–30°C and 33–35‰ salinity. *Portunus sanguinolentus* and *Ranella olearium*, on the other hand, show flat responses (EDF≈1, $p>0.05$), indicating extensive environmental tolerance.

2. The vulnerability of the monsoon

   Anadara inequivalvis and *Babylonia spirata* show a steep fall from August to October, which is consistent with monsoon-season salinity changes and DO dips (<4 mg/L). They are bioindicators of ecosystem stress because of their strong positive DO effects ($p<0.01$), which validate hypoxia sensitivity.

3. Exclusion from Competition

   While *A. inequivalvis*, its rival, flourishes in warmer, saltier environments, *Anadara indica* exhibits no significant responses (all $p>0.2$). The reduced abundance of *A. indica* can be explained by the fact that it is outcompeted when temperatures rise over 26 °C or salinity falls below 32‰.

Responses are further distinguished by the EDF values (Table 3):

- Complex non-linear interactions (EDF>2, such as the temperature response of Balanus) suggest sudden collapse over thresholds.
- Gradual changes are indicated by linear responses (EDF≈1, such as the Neverita DO effect).

These results indicate that specialists (Ergaea, Balanus) are at risk from climate change, whereas generalists (Ranella, Portunus) may become increasingly dominant amid growing environmental variability. Protecting high-DO refugia for species sensitive to hypoxia during monsoon seasons should be the top priority for management.

4. Discussion

Around the world, sandy beaches are the most prevalent kind of open coastline. Sandy beaches are dynamic, naturally occurring transitional, and their ecosystems are primarily shaped by physical factors like wind patterns, wave intensity, and tidal regime (Bozzeda *et al*., 2023). According to Harris and Defeo (2022), beaches in coastal areas supply 67% of known ecosystem services, with 50% of these functions being ascribed to beach biota. Beaches' ability to provide coastal protection is hampered by anthropogenic activities (Bozzeda *et al*., 2025). In all aquatic environments, hydrographical and physical factors influence the structure of the benthic community. The spatial patterns of species distribution, such as in estuary and coastal waters, can be significantly influenced by environmental variable gradients (Li *et al*., 2020).

The current study examines spatial and temporal variation in macrobenthic assemblages and environmental factors. The macrobenthic communities of Clifton beach mostly consist of polychaetes, molluscs, and crustaceans, which are considered as good bioindicators. Littoral macrobenthic communities, which are primarily made up of crustaceans, molluscs, and polychaetes, are seen to be the most trustworthy biological markers for assessing the ecological health of beaches (Martin *et al*., 2005). Only a few individuals of several species were found, although the majority of individuals belonged to a few abundant species.

A total of 8 mollusc species were identified during the current study, compared to 25 previously identified by Arshad and Farooq (2018) and 11 by Ahmed and Hameed (1999). Although 4 bivalves and 4 gastropod species were found in the present study, the abundance of bivalve group was more than that of gastropods. Similar results reported by (Arshad and Farooq, 2018; Liu *et al*., 2023). Bivalves' increased species number is likely related to their feeding method. According to Barnes (1987), bivalves are filter feeders with well-developed gills and primarily feed on phytoplankton, such as diatoms. In contrast, gastropods are generally scavengers that feed on polychaetes, crustaceans, and fish carrion. Several environmental elements in coastal waters seem to work together to influence the spatial organisation of molluscan communities (El Asri *et al*., 2021).

In the present study, the gastropod *Babylonia spirata* and the crustacean *Balanus trigonus* were the most common taxa, however, their relative abundance varied depending on the season. The most common species, *Babylonia spirata* (127.1 ± 54.6) and *Balanus trigonus* (mean 188.3 ± 72.5), attain their maximum abundance in March (297 individuals) and June (198 individuals), respectively. Due to ideal pre-monsoon (March) conditions, Clifton's high macrobenthos abundance this month. Similar results were also reported by Arshad and Farooq (2018) that the excellent pre-monsoon (March) circumstances were the reason for the high macrobenthos abundance at Clifton. These high numbers are most likely the result of favourable conditions like warmer temperatures, availability of more plankton, or summer-time (March–August) reproductive cycles. Higher temperatures, salinities, and oxygen levels are favourable for *Balanus trigonus* and *Ergaea walshi*. Both species peaking between 27 and 30°C and 33 and 35‰ salinity. Strong, non-linear responses (high EDF >2) to all predictors are shown by *Ergaea walshi* and *Balanus trigonus*, suggesting limited optimal ranges. Beyond these parameters, their abundance declines. Extremely sensitive species react the most strongly. The robust positive responses of *Ergaea walshi* suggest that it is very responsive to favourable circumstances. *Balanus trigonus* exhibits very high positive relationships with all three environmental parameters, but its non-linear responses to temperature (EDF=2.94, $p<0.001$) and salinity (EDF=2.52, $p=0.0006$) are most significant. Likewise, *Babylonia spirata* responds very favourably to all factors and has strong non-linearity in its salinity response (EDF=2.54). These patterns suggest that these species are very good bioindicators of favourable environmental conditions, and their abundance maxima most likely reflect ranges that are optimal for physiological performance.

According to Diaz and Sollow (1999), temperature, dissolved oxygen, and salinity variations in seawater ultimately impact the organisation of macrobenthic communities. More selective responses are displayed by Anadara species with moderate sensitivity. *Anadara inequivalvus* responds well to all three variables and in warm, high-salinity environments, *Anadara inequivalvis* predominates, but *Anadara natalensis* only reacts to temperature and dissolved oxygen. This variation within the same genus indicates niche divergence among these closely related species. *Anadara natalensis* shows a temperature specialist pattern that indicates salinity tolerance but thermal adaptation, with no apparent salinity response. No significant responses are shown by *Anadara indica* (all $p>0.2$). The fact that *Anadara indica* is outcompeted when temperatures rise beyond 26 °C or salinity drops below 32 ‰ decreased its abundance. Both biotic factors such as food, competition, and predation, and abiotic factors such as temperature, salinity, dissolved oxygen, and substrate, affect aquatic organisms. These environmental factors can impact the development, reproduction, and distribution of Anadara species (Sahin *et al*., 2006). In present study from August to October, *Anadara inequivalvis* and *Babylonia spirata* exhibit a sharp decline, due to changes in salinity during the monsoon season and DO drops (4 mg/L). However, their high positive DO effects ($p<0.01$) confirm hypoxia sensitivity, making them bioindicators of ecosystem stress.

The triton shell *Ranella olearium*, bivalve *Mactra antiquata*, and the crab *Portunus sanguinolentus* show no significant associations with any of the factors that were analysed, suggesting that they are either highly sensitive to unmeasured stimuli or have a broad tolerance range. The moon snail, *Neverita didyma*, has relatively mild positive tendencies, which suggests a weak environmental interaction. According to Ni *et al*. (2011), seasonal migration and the need for reproduction may be linked to temporal and spatial changes. This study showed that the macrobenthic community structures in the coastal waters of Clifton, Karachi, were influenced by both ecological and environmental parameters, such as temperature, salinity, and dissolved oxygen.

Conclusion

In the coastal waters of Clifton, Karachi, Pakistan, this study examined the species composition, biomass, and abundance of macrobenthic communities. It also examined ecological and environmental factors and their relationship to the organisation of macrobenthic communities. According to environmental factors and the monsoon season, the results of the present study demonstrate spatiotemporal fluctuations in macrobenthic communities and abundance. After identifying spatial and temporal communities, the community structure showed the strongest correlation with environmental variables: temperature, salinity, dissolved oxygen, and monsoon season. The coastal waters of Clifton, Karachi, should be properly managed and protected since they provide an ideal environment for the development of commercially significant benthic molluscs and crustaceans.

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Conflicts of Interest

All authors declare no conflict of interest.

References

Alsaid, T., Alsinani, M., and Ross, S. 2024. The endangered Arabian tahr observed drinking seawater in Oman. Journal of Arid Environments, 223: 105177.

Banwell, D.B. 2009. The sika in New Zealand. In Sika deer: biology and management of native and introduced populations, pp. 643–656. Eds. by D. McCullough, S. Takatsuki, and K. Kaji. Springer, Tokyo. 664 pp.

Bartoš, L. 2009. Sika deer in continental Europe. In Sika deer: biology and management of native and introduced populations, pp. 573–594. Eds. by D. McCullough, S. Takatsuki, and K. Kaji. Springer, Tokyo. 664 pp.

Borer, E.T., Lind, E.M., Firn, J., Seabloom, E.W., Anderson, T.M., Bakker, E.S., and *et al.* 2019. More salt, please: global patterns, responses and impacts of foliar sodium in grasslands. Ecology Letters, 22(7): 1136–1144.

Castellini, M., and Mellish, J.-A. 2023. Physiology of marine mammals: adaptations to the ocean. CRC Press.

Feldhamer, G.A., and Demarais, S. 2009. Free–Ranging and Confined Sika Deer in North America: Current Status, Biology, and Management. In Sika deer: biology and management of native and introduced populations, pp. 615–641. Eds. by D. McCullough, S. Takatsuki, and K. Kaji. Springer, Tokyo. 664 pp.

Iijima, H., Nagata, J., Izuno, A., Uchiyama, K., Akashi, N., Fujiki, D., and *et al.* 2023. Current sika deer effective population size is near to reaching its historically highest level in the Japanese archipelago by release from hunting rather than climate change and top predator extinction. The Holocene, 33(6): 718–727.

Masters, D.G., Rintoul, A.J., Dynes, R.A., Pearce, K.L., and Norman, H.C. 2005. Feed intake and production in sheep fed diets high in sodium and potassium. Australian Journal of Agricultural Research, 56(5): 427–434.

Michell, A.R. 1989. Physiological aspects of the requirement for sodium in mammals. Nutrition research reviews, 2(1): 149–160.

Mori, T., Iwagami, S., Yamagawa, H., and Suzuki, K.K. 2023. Do feed plants provide sufficient sodium, calcium, and magnesium to sika deer in Japan? An analysis using global plant trait data. Animals, 13: 1044.

Ohashi, H., Yoshikawa, M., Oono, K., Tanaka, N., Hatase, Y., and Murakami, Y. 2014. The impact of sika deer on vegetation in Japan: setting management priorities on a national scale. Environmental Management, 54(3): 631–640.

Pompa, S., Ehrlich, P.R., and Ceballos, G. 2011. Global distribution and conservation of marine mammals. Proceedings of the National Academy of Sciences, 108(33): 13600–13605.

Runa, R.A., Brinkmann, L., Gerken, M., and Riek, A. 2019. Adaptation capacity of Boer goats to saline drinking water. Animal, 13(10): 2268–2276.

Schipper, J., Chanson, J.S., Chiozza, F., Cox, N.A., Hoffmann, M., Katariya, V., and *et al.* 2008. The status of the world's land and marine mammals: diversity, threat, and knowledge. Science, 322(5899): 225–230.

Suzuki, K.K., Watanabe, Y., Kubota, T., Kuwano, Y., Kawauchi, Y., Yamagawa, H., and *et al.* 2021. Large-scale spatial distribution of deer browsing damage to young tree plantations. iForest, 14(1): 34–40.

Suzuki, K.K., Kuwano, Y., Kanamori, Y., Kawauchi, Y., Uchimura, Y., Yasuda, M., and *et al.* 2022a. A 25-year study of the population dynamics of a harvested population of sika deer on Kyushu Island, Japan. Forests, 13(5): 760.

Suzuki, K.K., Oka, T., and Yasuda, M. 2022b. Spatiotemporal changes in antlerless proportion of culled Sika deer in relation to deer density. Journal of Forestry Research, 33(3): 1095–1101.

Suzuki, K.K., Mori, T., and Yamagawa, H. 2023. Sex differences in a large herbivore's salt water drinking behaviour: a method for applying a female-biased attractant. Mammal Research, 68: 653–658.

Suzuki, K.K., Mori, T., and Yamagawa, H. 2024. Seasonal change in attractiveness of salt water on female deer. European Journal of Wildlife Research, 70(4): 65-78.

Swanson, GM., and Putman, R. 2009. Sika deer in British Isles. In Sika deer: biology and management of native and introduced populations, pp. 595–614. Eds. by D. McCullough, S. Takatsuki, and K. Kaji. Springer, Tokyo. 664 pp.

Yamagawa, H., Kitahara, F., Otani, T., Yoneda, R., Suzuki, K.K., and Nomiya, H. 2023. Assessing the damage caused by deer on young trees in a Sugi (*Cryptomeria japonica*) plantation based on field signs. Journal of Forest Research, 28: 194–203.