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Clam population ecology in relation to environmental characteristics: A comparative assessment of Tuticorin Bay and Pazhayakayal Estuary, south-east coast of India

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Abstract

A study was undertaken to assess the population characteristics of clams and their relationship with physicochemical parameters in two ecosystems of Thoothukudi coast *viz*. Tuticorin Bay and Pazhayakayal Estuary, from July 2021 to May 2022. The study was based on monthly sampling of clam populations and associated physicochemical parameters at three stations (St. 1, St. 2 and St. 3) in each of the two locations. In Tuticorin Bay, the total clam density ranged from 16 (TB-3) to 148 nos. m^{-2} (TB-2) with the mean density of 65±3.3 nos. m^{-2}. Among the species, *Meretix casta* was dominant (33%) followed by *Gafrarium pectinatum* (24%), *Marcia opima* (22%), *Paphia malabarica* (21%), and *Meretrix meretrix* (<1%). The total clam density of Pazhayakayal Estuary ranged from 72 (PE-2) to 632 nos. m^{-2} (PE-3) with a mean of 311±38 nos. m^{-2}. Both biomass and density of the clams significantly varied between the stations of Tuticorin Bay ($p<0.01$), whereas at Pazhayakayal Estuary, both parameters were not significantly different ($p>0.05$). The study further revealed that in Tuticorin Bay, characterised by fine sandy substrates (ranging from 35.01 to 81.62%) with relatively high organic carbon content (0.110 to 0.751%), supported greater species diversity but lower population density. In contrast, the Pazhayakayal Estuary, characterised by coarse sand (13.29 to 77.65%) and hyposaline conditions, supports a high population density dominated by a single species *M. casta*. .

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Introduction

Bivalve resources comprising clams, cockles, oysters and mussels are distributed throughout the Indian coast including the estuaries and backwaters and are commercially exploited by the local fishers for their sustenance. Indian export of bivalves comprises mainly clam and mussel meat (Mohamed, 2013). In ecological research, the distribution of species in nature in relation to the various environmental conditions still leaves a critical issue. By looking at the interactions between environmental factors and benthic community structures, benthic ecologists formulate their theories about the ecological processes. The species diversity, biomass, and population density of soft bottom macrofauna are all influenced to varying degrees by environmental factors. Environmental factors play an important role in regulating the distribution and abundance of the bivalves in the ecosystem (Soares-Gomes and Pires-Vanin, 2005; McLeod and Wing, 2008). Estuarine ecosystems are perfect for studying such interactions, because of the rich abiotic characteristics (Tanyaros and Tongnunui, 2011). An estuary is a unique area exhibiting environmental and biological gradients. Each species of estuary has an ideal niche along a gradient, and these species are found along biological and environmental gradients. Research by Macfarlane and Booth (2001), Morrisey *et al.* (2003), Currie and Small (2005), Nouri *et al.* (2008), and Aweng *et al*. (2012) demonstrated the strong relationship between environmental conditions and macrobenthos distributional patterns. Environmental factors like salinity

(McLusky, 1968; Holland *et al*., 1987; Maes *et al*., 1998; Cervetto *et al.*, 1999), tidal level (Warwick and Uncles 1980), biotic interactions (Wilson Jr, 1991), perturbation (Diaz and Rosenberg, 1995), or sediment characteristics (Chapman and Tolhurst, 2004; Ampili and Sreedhar, 2016) have all been linked to variations in the abundance and distribution patterns of bivalves within estuarine systems. As a transitional area between land and sea, bays are rich in resources such as marine life and ocean floor minerals (Sun *et al.,* 2020). Tuticorin Bay has got its natural recruitment of bivalves as well as gastropods and supports a heterogeneous population of molluscan fauna. The catch of bivalve molluscs represents one of the most important artisanal fisheries in Tuticorin Bay and Pazhayakayal Estuary. The biomass of bivalves in the ecosystem must be monitored to ensure sustainable fishery and stock conservation. Understanding the biology and physiology of the species as well as the environmental factors influencing its population dynamics are necessary for managing fisheries while preserving biodiversity and upholding healthy ecosystems (McLachlan *et al*., 1995; Howe *et al.,* 2007; Cacabelos *et al.,* 2008; La Valle *et al*., 2011: Tilburg *et al*., 2012). The understanding of how environmental factors influence recruitment success is crucial for effective fisheries management and for predicting stock dynamics of bivalve species. However information on clam population characteristics and the factors affecting them in the two contrasting ecosystems, viz., Tuticorin Bay and Pazhakayal Estuary of Tuticorin coast, is lacking. Therefore, the present study was undertaken to ascertain the causes of spacial and temporal variations in clam populations. These two ecosystmes were selected due to their contrasting environmental conditions (marine bay vs estuarine influence), which provide an opportunity to evaluate the role of physicochemical factors in shaping clam populations. Both areas also support important local bivalve fisheries, highlighting their ecological and economic significance.

Materials and methods

Study location

Two ecosystems *viz.* Tuticorin Bay and Pazhayakayal Estuary, with different geographical features were selected for the study which was undertaken during June 2021 to May 2022. Tuticorin Bay receives an inflow of freshwater from a small rivulet (Korampallam Creek) with a tidal amplitude of 1 m. Tuticorin Bay has got its natural recruitment of bivalves and gastropods which supports a heterogeneous population of molluscan forms. The three stations selected at Tuticorin Bay (Fig.1a) include St.1 (TB-1) (08°46'.757'N; 078°09'.621'E), Tuticorin Bay nearer to seawater intake point for mariculture activities of the Tuticorin Regional Station of ICAR-Central Marine Fisheries Research Institute, St.2 (TB-2) which is located at the northern side of the Bay nearer to the Korampallam freshwater creek (08°47'.002'N; 078°09'.598'E) and St.3 (TB-3) situated at the southern side of the Bay towards the Tuticorin Thermal Power Plant (TTPS), which is under the direct influence of the TTPS's discharge (08°46'.670'N; 078°09'.660'E). The distance between each sampling station is roughly around 50 m. Pazhayakayal Estuary is located 15 km away from Tuticorin and the estuary receives freshwater influx during south-west and north-east monsoon from Thamirabharani River which originates from Agastiar Mountain of Western Ghats, and drains into the Bay of Bengal at Punnaikayal and Pazhayakayal estuarine part of Gulf of Mannar. The three stations selected include St.1 (PE-1) (08°39.555'N; 078°06.828'E), located 2 km away from the fish landing centre with sandy bottom substratum, St.2 (PE-2) (08°39.585'N; 078°06.344'E) which is 1 km away from St. 1 and has edible oyster beds. St.3 (PE-3) (08°39.479'N; 078°06.029'E) is situated 0.73 km away from St. 2, which is impacted by the effluents from the nearby seafood exporting unit (Fig.1b).

Clam population were sampled using a square iron quadrat of 0.25 m^2. Sediment samples containing clams were collected sieved through a 5 mm mesh net to retain the specimens. Clam density and biomass were estimated, and the mean values from replicate three quadrat samples were used to calculate density and biomass per square metre (Ampili and Sreedhar, 2016).

Seawater and sediment analysis

Seawater and sediment samples were collected from all three stations of both the ecosystems during four different seasons: summer, pre-monsoon, monsoon and post-monsoon. Water quality parameters *viz.* dissolved oxygen (DO), carbon dioxide, biological oxygen demand (BOD), pH, salinity, chlorophyll, gross primary productivity (GPP), net primary productivity (NPP), ammonia, total suspended solids (TSS),

(a) (b)

Fig.1. Map showing sampling stations in the (a) Tuticorin Bay and (b) Pazhayakayal Estuary

total dissolved solids (TDS), alkalinity, and nutrients like nitrite (NO_2), nitrate (NO_3), phosphate (PO_4) and silicate (SiO_3) were estimated by standard methods. *In situ* measurements of early morning air temperature and sea surface water temperatures (AT and SST) were made using a high-precision thermometer. Salinity was determined by Mohr's titration method (Grasshoff *et al*., 1983). Dissolved oxygen and BOD were estimated by the modified Winkler's method (Strickland and Parsons, 1972). Ammonia was estimated by the phenol hypochlorite method (Solorzano, 1969), and the nutrients were determined using a spectrophotometer (Genesis 10 model) following the procedure given by Grasshoff *et al*. (2009). Primary production was estimated by the dark and light bottle method, and Winkler's method (1888) was employed to estimate the dissolved oxygen. The same was converted into carbon equivalent using a PQ of 1.25 for obtaining the gross production. Total chlorophyll was assessed according to Parsons *et al*. (1984). Total suspended and dissolved solids were estimated by filtration and alkalinity by titration method (APHA, 2005). Carbon dioxide concentration was quantified by the acid-base titrimetric method (Dickson, 1998).

A core sampler of 20 cm in length and 3 cm lumen diameter was used to collect subsurface sediment samples from all the stations. The samples were dried, pulverised and sieved to estimate sediment quality parameters. Sediment texture was analysed by the pipette method (Lewis, 1984). The bottom sediments organic carbon, organic matter and nitrogen were estimated by Walkley and Black (1934) method.

Statistical analysis

One-way analysis of variance (ANOVA) on all possible combinations was performed to test the significant seasonal and station-wise differences between parameters, using SPSS ver. 20 (Chicago, USA). Relationships between the population parameters and physicochemical variables were analysed by correlation based principal component analysis (PCA). The component matrix with the value of eigenvector (>±0.45) was selected and taken in the interpretation of results. All the univariate and multivariate analyses of data were done using PRIMER (Plymouth Routines in Multivariate Ecological Research) v.6.1.12 package developed by the Plymouth Marine Laboratory, UK (Clarke and Gorley, 2001).

Results and discussion

The physicochemical parameters displayed considerable variation among stations in Tuticorin Bay and Pazhayakayal Estuary (Table 1). The distribution of aquatic species is strongly influenced by environmental factors such as temperature, salinity, dissolved oxygen, transparency, pH, hardness and grain size of sediment (Prasanna and Ranjan, 2010; Ampili and Sreedhar, 2016). Analysis of physicochemical factors in relation to clam distribution and abundance revealed significant correlations between environmental conditions and biological responses. Correlation based principal component analysis (PCA) of physicochemical variables for Tuticorin Bay and Pazhayakayal Estuary is presented in Table 2.

Water quality parameters

Temperature

Sea surface temperature has been considered as an important variable influencing bivalve reproductive development and spawning (Gribben, 2005; Matozzo *et al*., 2013), and may even be a key factor

Table 1. Physiochemical parameters (Mean±SE) recorded in Tuticorin Bay and Pazhayakayal Estuary

Parameters	Tuticorin Bay			Pazhayakayal Estuary			p value
	TB-1	TB-2	TB-3	PE-1	PE-2	PE-3	
AT (°C)	28.38±0.44	28.88±0.53	28.75±0.59	30.45±0.51	30.75±0.48	30.09±0.41	0.003
SST (°C)	27.63±0.50	27.80±0.45	28.04±0.49	28.59±0.54	29.05±0.52	28.68±0.49	0.295
Salinity (ppt)	29.56±2.14	31.08±1.85	29.91±1.90	20.82±1.72	20.35±1.96	20.61±1.86	0.000
Alkalinity (mg l^{-1})	127.42±3.38	130.03±3.18	130.54±3.48	124.59±3.35	125.18±2.63	127.95±4.60	0.783
DO (ml l^{-1})	4.26±0.19	3.38±0.23	4.65±0.26	4.13±0.19	4.47±0.14	4.20±0.17	0.001
BOD (mg l^{-1})	1.58±0.11	1.58±0.15	1.47±0.15	1.36±0.14	1.19±0.13	1.45±0.14	0.369
GPP (mg C $l^{-1}d^{-1}$)	2004.06±281	2541.92±618	1945.75±183	2189.36±276	1943.91±165	2507.45±445	0.751
NPP (mg C $l^{-1}d^{-1}$)	1215.64±215	1721.48±528	1156.40±158	1514.86±304	1249.77±167	1556.62±338	0.767
NH_3 (µg l^{-1})	1.53±0.20	1.65±0.19	1.51±0.21	1.02±0.16	1.28±0.20	1.05±0.19	0.106
TSS (mg l^{-1})	0.36±0.02	0.36±0.01	0.36±0.01	0.32±0.03	0.31±0.03	0.35±0.05	0.567
TDS (mg l^{-1})	27.77±2.21	23.88±2.78	27.91±2.77	23.54±2.88	23.76±2.68	22.53±3.11	0.603
Chlorophyll (mg m^{-3})	1.55±0.37	2.35±0.65	1.31±0.57	1.59±0.50	1.69±0.48	1.38±0.27	0.712
NO_2 (µg l^{-1})	1.79±0.37	2.02±0.38	2.08±0.64	1.05±0.27	1.74±0.51	2.13±1.17	0.845
NO_3 (µg l^{-1})	3.56±0.47	4.19±0.47	3.22±0.41	2.25±0.26	3.00±0.51	3.04±0.50	0.079
PO_4 (µg l^{-1})	0.76±0.26	0.78±0.27	0.78±0.32	0.90±0.42	1.19±0.70	1.38±0.73	0.912
SiO_3 (µg l^{-1})	1.24±0.29	1.18±0.28	1.21±0.26	1.49±0.26	1.55±0.29	1.53±0.26	0.842

AT:Air temperature; SST: Sea surface temperature; DO: Dissolved oxygen; BOD: Biological oxygen demand; GPP: Gross primary productivity; NPP: Net primary productivity; NH_3: Ammonia; TSS: Total suspended solids; TDS: Total dissolved solids; NO_2: Nitrite; NO_3: Nitrate; PO_4: Phosphate; SiO_3: Silicate

Data are represented as the arithmetic mean of three replications ±SE. The parameter with $p<0.05$ is significantly different among the stations studied.

in certain species distribution. The sea surface temperature of Tuticorin Bay varied from 27.6°C at TB-1 to 28.0°C at TB-3. In the Pazhayakayal Estuary, it ranged between 28.5°C (PE-1) and 29.0°C (PE-2). In the present study, not much variation was observed in the sea surface temperatures between the stations of Tuticorin Bay and Pazhayakayal Estuary. Sea surface temperature of both Tuticorin Bay and Pazhayakayal Estuary, positively influences the clam density and biomass. According to Queiroga *et al*. (2007) higher temperatures enhance the larval growth rates and reduce the time interval between spawning and benthic settlement. Temperature has been suggested to be the main factor limiting the distribution of temperate bivalves (Manzi and Castagna, 1989). de Almeida *et al*. (2021) found a positive correlation between sea surface temperature and biomass for the species *Spisula solida* in the Algarve, south coast of Portugal.

Salinity

The salinity of Tuticorin Bay varied from 7.96 at TB-1 to 35.5 ppt at TB-2. The highest mean salinity of 31.08±1.9 ppt was recorded at TB-2 of Tuticorin Bay. Water was comparatively hypo-saline throughout at Pazhayakayal Estuary and ranged from 9.92 to 32.1 ppt at PE-3. The analysis of variance showed significant variation in the values of salinity between the stations of both Tuticorin Bay and Pazhayakayal Estuary. The freshwater influx impacted both ecosystems. The year-round freshwater flow from the Thambirabarani River is responsible for the hyposaline water in Pazhayakayal Estuary, while the freshwater influx during the north-east Monsoon impacted the Tuticorin Bay. Correlation studies revealed that the salinity has a significant negative correlation with clam density in both Tuticorin Bay (-0.217) and Pazhayakayal Estuary (-0.118). Salinity is an important environmental factor that influences the physiological responses and distribution of marine and estuarine organisms. The response of bivalve species to varying salinity ranges have been well documented (Harkantra and Rodrigues, 2004; Tanyaros and Tongnunui, 2011; Ampili and Sreedhar, 2016). According to Ram Mohan and Velayudhan (1998), *Paphia malabarica* can tolerate salinity levels ranging from 12 to 40 ppt. In the Chettuva Estuary, clam distribution is influenced by salinity, with *M. casta* showing a preference for salinity levels between 20 and 33 ppt (Laxmilatha *et al*., 2006a). Similarly, *P. malabarica* has been reported as the dominant species contributing to bivalve biomass in various stations of the Ashtamaudi Lake at salinities ranging from 29 to 34 ppt, while *M. casta* predominates in the middle regions of the lake, where salinity ranges from 23 to 29 ppt (Appukuttan *et al.,* 2002). According to Ampili (2014), *P. malabarica* (10.515 to 31.195 ppt) and *M. casta* (10.793 to 29.295 ppt) are capable of tolerating a wide range of salinity conditions in Ashtamudi Lake. These findings highlight the adaptive capacity of these species to fluctuating salinity regimes in estuarine ecosystems.

Dissolved oxygen (DO)

Dissolved oxygen (DO) in estuarine systems is regulated by multiple processes, including photosynthesis, respiration, and transport through tidal exchange (Iriarte *et al.,* 2015; Lake and Brush 2015; Murrell *et al.,* 2018). In the present study, DO exhibited considerable spatial variation across both ecosystems ranging from 2.17 to 5.73 ml l^{-1} in Tuticorin Bay and from 3.35 to 5.34 ml l^{-1} in Pazhayakayal Estuary. The highest mean DO values were recorded at station TB-3 (4.31±0.21 ml l^{-1}) in Tuticorin Bay and at station PE-2 (4.4±0.21 ml l^{-1}) in Pazhayakayal Estuary (Table 1). The DO showed a positive correlation with clam density in both Tuticorin Bay (r=0.215) and Pazhayakayal Estuary (r=0.168). Significant spatial variation in DO concentration was observed among stations in both ecosystems. Similar relationships have been reported elsewhere; for *e.g.* DO exhibited a strong positive connection (r=0.68) with the biomass of black clam (*Villorita cyprinoides*) in the Vembanad Estuary (Theresa Paul *et al.,* 2017). In the Ashtamudi Estuary, DO showed a significant negative correlation with the density of *P. malabarica* (r=-0.227) and a significant positive correlation with *M. casta* (r=0.228) (Ampili, 2014).

Total suspended solids (TSS) and total dissolved solids (TDS)

Relatively minor fluctuations were noticed in the TSS and TDS concentrations between the two ecosystems. TSS values ranged from 0.23 to 0.46 mg l^{-1} and 0.20 to 0.55 mg l^{-1} in Tuticorin Bay and Pazhayakayal Estuary, respectively. The mean TDS was higher in Tuticorin Bay compared to the Pazhayakayal Estuary. The relatively lower TDS may have contributed to the higher bivalve density in Pazhayakayal Estuary. Similar observations have been reported by Theresa Paul *et al.* (2017), who observed a strong positive correlation (r=0.68) between water transparency and black clam (*V. cyprinoides*) biomass in the Vembanad Estuary.

Primary productivity and total chlorophyll

The highest mean gross primary productivity (GPP) and net primary productivity (NPP) in Tuticorin Bay were recorded at station TB-2 with values of 2541.9±618.8 mg C m^{-3} d^{-1} and 1721.5±528.8 mg C m^{-3} d^{-1}, of respectively. In Pazhayakayal Estuary, the highest mean GPP (3320.3±508.9 mg C m^{-3} d^{-1}) and NPP (2101.3±400.2 mg C m^{-3} d^{-1}) were recorded at PE-3. Total chlorophyll concentrations were comparatively higher in Tuticorin Bay, with the highest mean value of 2.35±0.65 µg l^{-1} at station TB-2, whereas in Pazhayakayal Estuary, the highest mean value was 2.43±0.65 µg l^{-1} at PE-2. In both the ecosystems, GPP and NPP exhibited a negative relationship with clam density, whereas total chlorophyll showed contrasting patterns with positive correlation (r=0.234) with clam density in Pazhayakayal Estuary and negative correlation (r=-0.219) in Tuticorin Bay. Food availability plays a crucial role in influencing reproductive processes in clams, often leading to early spawning and enhanced larval survival (Gaspar *et al.,* 2004; Ojea *et al.,* 2004; Albentosa *et al.,* 2007, Maunder and Deriso, 2013) under favourable conditions. Consistent with the present findings, Sivashankar *et al.* (2015) found a positive relationship between *M. casta* and chlorophyll in the Mulki Estuary, while Nagvenkar *et al.* (2014) observed higher densities of *P. malabarica* associated with lelevated levels of chlorophyll during the pre-and post-monsoon seasons. Similarly De Almeida *et al.* (2021) reported that bivalve populations (*Spisula solida, Chamelea gallina,* and *Ensis siliqua*), along the Barlavento coast of Portugal were positively influenced by the chlorophyll-α concentrationsbetween May and October. However, *Donax trunculus* exhibited a negative relationship with chlorophyll-α during the spawning season, likely due to prevailing unfavourable wind conditions rather than a direct response to increased primary productiviry.

Biological oxygen demand (BOD)

At Tuticorin Bay, the BOD ranged between 0.8 and 2.40 mg l^{-1} and the highest mean of 1.58±0.15 mg l^{-1} was noticed at TB-2. In contrast, at Pazhayakayal stations, the BOD varied between 0.6 and 2.5 mg l^{-1} and the highest mean of 1.68±0.18 mg l^{-1} was recorded at PE-3. BOD was found to positively impact the clam density of both Tuticorin Bay and Pazhayakayal Estuary. According to Prandi-Rosa and Farache Filho (2002) and Wahid *et al.* (2007), waters with BOD levels greater than 10 mg l^{-1}, are considered highly polluted, indicating elevated levels of degradable organic matter. In contrast, waters with BOD levels below 4 mg l^{-1} (Prandi-Rosa and Farache Filho, 2002) or 5 mg l^{-1} (Sadhuram *et al.,* 2005) are deemed reasonably clean. Filter feeding organisms such as bivalves are comparatively less affected by variations in BOD (Konrad, 2014; Jayachandran *et al.,* 2019), and many species can tolerate conditions where BOD exceeds typical thresholds. This resilience is attributed to their physiological adaptability and contributes to their effectiveness as bioindicators of environmental quality (Liyana *et al.,* 2019).

Alkalinity

Alkalinity exhibited relatively low variation across all sampling stations. Values ranged from 103.4 to 152.9 mg l^{-1} in Tuticorin Bay and from 107.7 to 152.9 mg l^{-1} in Pazhayakayal Estuary. The highest mean alkalinity values were recorded at TB-3 (132.5±4.41 mg l^{-1}) in Tuticorin Bay and at PE-3 (134.4±4.96 mg l^{-1}) in Pazhayakayal Estuary. PCA indicated a negative impact of alkalinity on the clam density in both ecosystems (Table 2) . However, the alkalinity levels recorded at all the stations in the present study, remained well within the safe limit of 600 mg l^{-1} for marine organisms. Elevated alkalinity levels can adversely affect clam physiology and consequently their survival and growth. Similar effects of high alkalinity on the survival and growth of clams such as *Cyclina sinesis* (Lin *et al.,* 2013) and *Sinonovacula constricta* (Maoxiao *et al.,* 2018) have been demonstrated.

Nutrients

Ammonia concentration was comparatively higher at all stations in Tuticorin Bay and ranged between 0.13 to 2.6 mg l^{-1} at TB-3. At Pazhayakayal Estuary, the ammonia levels ranged between 0.16 mg l^{-1} at St.1. to 1.85 mg l^{-1} at PE-2. At Tuticorin Bay, nutrients like NO_2, PO_4 and SiO3 were comparatively higher at TB-3, whereas NO_3 was highest at TB-2. The highest mean values of 2.97±0.73 µg l^{-1} for NO_2; 1.02 ±0.42 µg l^{-1} for PO_4 and 1.36±0.32 µg l^{-1} for SiO_3 were recorded at TB-3. The highest mean NO_3 value of 4.19 ±0.47 µg l^{-1} was observed at station TB-2 in Tuticorin Bay.

At Pazhayakayal Estuary, the NO_2 and PO_4 levels were comparatively higher at PE-3. The highest mean values of NO_2 (3.19±1.82 µg l^{-1}) and PO_4 (2.03±1.13 µg l^{-1}) were also noticed at PE-3. The highest mean SiO_3 level (1.49±0.30 µg l^{-1}) was observed at PE-1 and NO_3 (2.49±0.58 µg l^{-1}) at St.2. Except for SiO_3, all other nutrients (NO_2, NO_3 and PO_4) showed negative influence on the clam density in both Tuticorin Bay and Pazhayakayal Estuary. In the present study, high concentrations of all the nutrients were observed at stations in both Tuticorin Bay and Pazhayakayal Estuary, in concordance with high clam density, which could be attributed to the effect of increased excretion rate by clams. Asmus and Asmus (1991) and Nakamura and Kerciku (2000) have also ascertained the role of bivalve excretion in nutrient recycling of marine environment.

Sediment quality parameters

Substratum

The physical nature of the substratum varied markedly between Tuticorin Bay and Pazhayakayal Estuary. In Tuticorin Bay, most of the clam beds are exposed to tidal currents and the sediments are predominantly composed of fine sand, followed by coarse sand, silt and clay. The proportion of fine sand varied between 30.09 to 81.62%, with the highest mean value (68.35±3.16 %) noticed at TB-1 (Fig. 2). The dominance of fine sand appears to play a significant role in influencing clam distribution across stations in Tuticorin Bay. In contrast, clam beds in the Pazhayakayal Estuary remain submerged throughout the tidal cycle, with depths ranging from 1 to 2.5 feet during low tide. At Pazhayakayal Estuary, coarse sand was the major constituent of the bottom sediments at a proportion of 29.53 to 77.65%, and the highest mean proportion (68.8±3.28%) was noticed at PE-3 (Fig. 3). Here fine sand was the second major constituent, followed by silt and clay. Significant difference in the soil

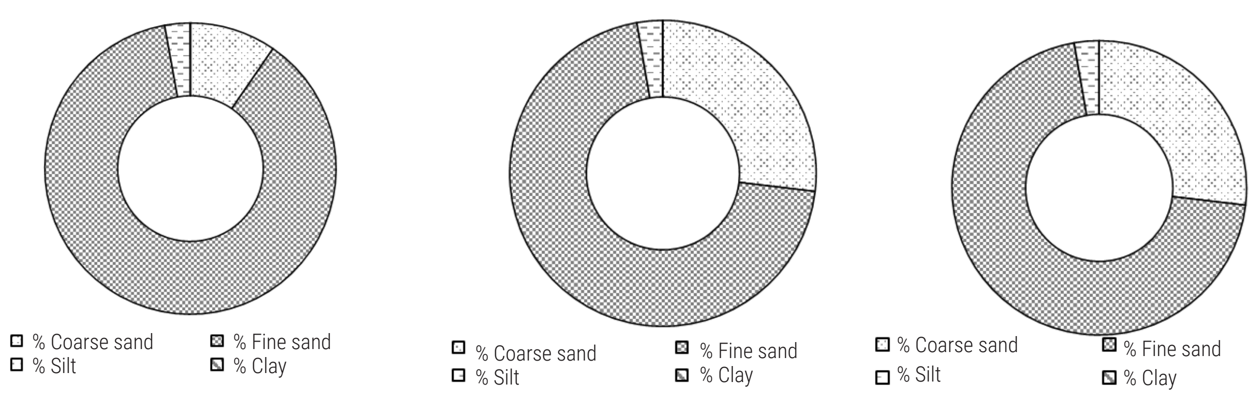

Fig. 2. Sediment texture at three stations (a.) TB-1); (b) TB-2; (c)TB-3 of Tuticorin Bay

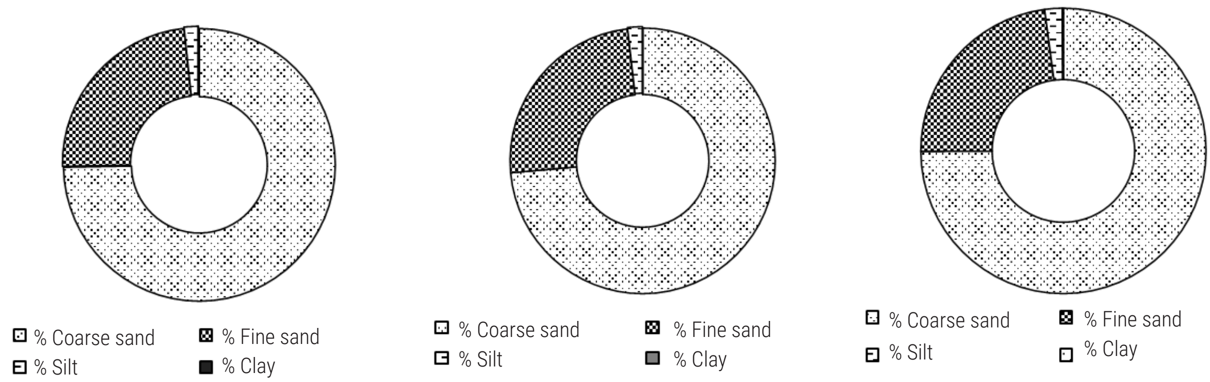

Fig. 3. Sediment texture at three stations (a) PE-1; (b) PE-2; (c) PE-3 of Pazhayakayal Estuary

texture was noticed between both the ecosystems and also there was a significant variation between the stations of Tuticorin Bay. Sediment type and grain size also have been major factors affecting community diversity and abundance (Lin *et al.,* 2018). Previous studies have reported varying substrate preferences among clam species. For *e,g*, (*P. malabarica* has been shown to predominantly inhabit sandy substrates with sand (40.94±0% to 98.72±0.01%) forming the predominant component of its beds in the Zuari and Mandovi estuaries, Goa (Nagvenkar *et al.,* 2014). Similarly, Parulekar *et al.* (1984), reported a significant association of *P. malabarica* with sandy sediments (r=0.38, p<0.05). The findings of Sivashankar *et al*. (2015) indicated a positive link between *M. casta* and substratum, specifically clay, coarse sand and very fine sand. On the other hand, *P. malabarica* showed a positive relation with medium, fine, and very fine sand from the Mulki Estuary and a negative correlation with sand and coarse sand. In the Vellar Estuary, *M. casta* appears to favour the sandy-silt substratum (Balasubrahmanyam and Natarajan, 1987). In the Chettuva Estuary, clam distribution is influenced by substrate, with *M. casta* favoring sandy bottoms (Laxmilatha *et al.,* 2006 b). *P. malabarica* showed a predilection for a sandy clay substratum, but *M. casta* was found to prefer more fine sand. *M. casta* showed a positive link with sand, clay coarse sand, and very fine sand and on the other hand, *P. malabarica* showed a positive relation with medium, fine, and very fine sand and a negative correlation with coarse sand (Sivashankar *et al*., 2015).

Organic matter

Organic matter is an essential component of the estuarine and coastal sediments and plays a significant role in the food web (Zimmerman and Canuel, 2001). The abundance of organic matter in the substratum is reported to be instrumental in determining the stability of the clam bed. Estuarine sediment is enriched with organic matter from a variety of sources, including land runoff, industrial and domestic waste, and allochthonous inputs from river discharge (Meziane and Tsuchiya, 2002; Hu *et al.,* 2006; Dunn *et al.,* 2008; Fuller, 2021). The organic carbon, organic matter and N_2 content in the bottom soil were also comparatively higher at Tuticorin Bay and they were positively influencing the clam density of this ecosystem. Here, the highest mean values of 0.423±0.05%, 0.73±0.09%, and 0.021±0.003% respectively for organic carbon, organic matter, and N_2 respectively were recorded at station TB-3. In Pazhayakayal Estuary, the highest mean values of 0.156±0.027%, 0.269±0.047% and 0.007±0.001% for organic carbon, organic matter and N_2 respectively were found at station PE-3. The organic matter did not show any positive influence on clam density at Pazhayakayal Estuary. Organic matter, organic carbon and N_2 significantly varied between the stations of both Tuticorin Bay and Pazhayakayal Estuary (Fig. 4). Spatial distribution studies in the Algarve coast indicated that sediment and proximity to river input influenced bivalve distribution (Martins *et al.,* 2014). When sediment total organic carbon exceeded 1.0-1.5%, the benthic species diversity reduced

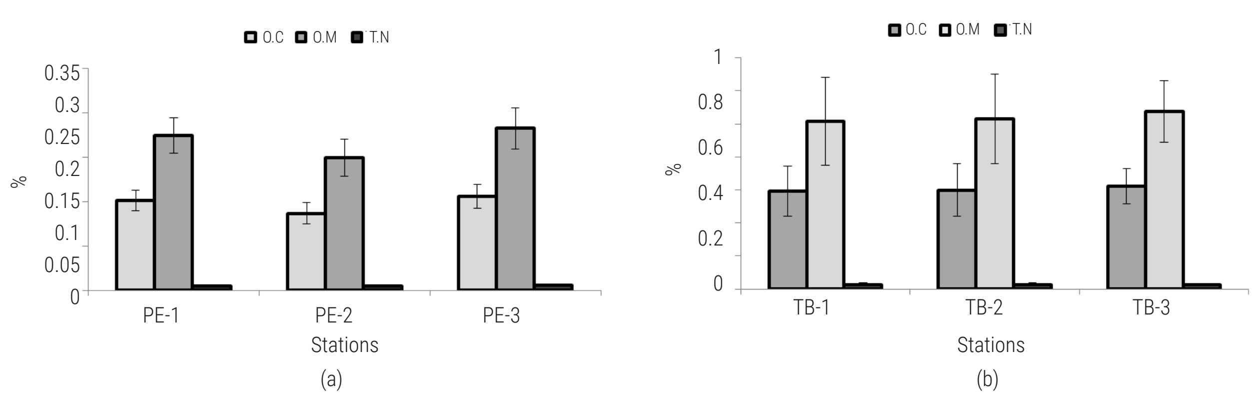

Fig. 4. Percentage of sediment organic carbon (OC), organic matter (OM) and total nitrogen (TN) at three stations of (a) Tuticorin Bay and (b) Pazhayakayal Estuary

(Burd *et al.,* 2008). Species diversity and abundances also decreased when concentrations of sediment total nitrogen exceeded 0.4% (Burd *et al.,* 2008). Though Tuticorin Bay has high organic matter compared to the Pazhayakayal Estuary, in both ecosystems, organic carbon and sediment nitrogen were within the safe limits.

Abundance and distribution of clams

In Tuticorin Bay, the clam density was found highest (148 nos. m^{-2}) at TB-2 and the lowest (16 nos. m^{-2}) at TB-3 with a mean density of 65±3.3 nos. m^{-2}. At TB-1, the population density of clams varied from 28 to 76 nos. m^{-2} (57±4.8 nos. m^{-2}) and the biomass varied from 417 to 1520 g m^{-2} (1001±91 g m^{-2}). At TB-2, the clam density and biomass ranged from 44 to 148 no m^{-2} (87±8.79 nos. m^{-2}) and 686 to 2366 g m^{-2} (1524±149 g m^{-2}) respectively. The clam density of TB-3 ranged between 16 and 116 nos. m^{-2} (49±8.02 nos. m^{-2}) and biomass varied from 238 to 1891 g m^{-2} (873±141 g m^{-2}). Both biomass and density of the clams were significantly different between stations of Tuticorin Bay ($p<0.01$). The spatial distribution of clam populations can change in response to a variety of environmental factors. Physical, chemical, and biological interactions affect the growth and survival of clams in the clam beds. At Tuticorin Bay, significant differences in the dissolved oxygen content and soil texture between stations might have influenced the distribution and density of clams.

The highest clam density in Pazhayakayal Estuary was noticed at PE-3 (632 nos. m^{-2}) and the lowest at PE-2 (72 nos. m^{-2}) with a mean of 311±38 nos. m^{-2}. At PE-1, the clam density and biomass ranged from 88 to 632 nos. m^{-2} (321±50 nos. m^{-2}) and 1804 to 12,823 g m^{-2} (6335±1001 g m^{-2}) respectively. At PE-2, the density ranged from 72 to 428 nos. m^{-2} with a mean density of 268 ± 34 nos. m^{-2} and biomass ranged from 1476 to 8646 g m^{-2} (5326±684 g m^{-2}). The clam density of PE-3 ranged between 92 and 556 nos. m^{-2} (345±50 nos. m^{-2}) and the biomass between 1886 and 13066 g m^{-2} (6879±1068 g m^{-2}). Both biomass and density of the clams were not significantly different between stations. The mean clam biomass of Tuticorin Bay and Pazhayakayal Estuary is depicted in Fig. 5.

The clam density and biomass have been widely studied from various estuaries of India by several authors and variable results have been reported. The maximum clam density (15,558 nos. m^{-2}) reported

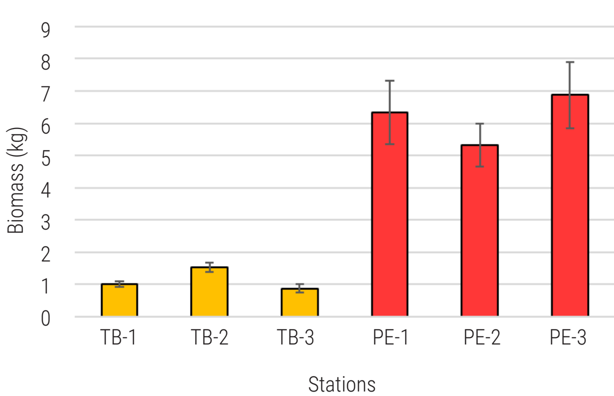

Fig. 5. Clam biomass in different stations at Tuticorin Bay and Pazhayakayal Estuary

in Indian waters was for *V. cyprinoides* in Vembanad Lake (Vijaya-Krishna and Ammini, 2018). Appukuttan *et al.* (2002) recorded higher clam density in the Astamudi Lake, Kerala which ranged between 59 and 3732 nos. m^{-2}, with the dominance of *P. malabarica* followed by *V. cyprinoides* and *M. casta*. Balasubrahmanyam and Natarajan (1987) studied the distribution of *M. casta* and reported a density ranging from 389 to 1747 nos. m^{-2} in the Vellar Estuary, Tamil Nadu which is higher than the *M. casta* density recorded from Pazhayakayal Estuary. Similarly, high clam density was observed by Laxmilatha *et al*. (2011) in Moorad Estuary, Kerala, where the average density of clams *M. casta* and *M. meretrix* were 1096 nos. m^{-2} and 96 nos. m^{-2} respectively. In Kerala, the mean density of *P. malabarica* in Ashtamudi Estuary was recorded as 248±55 nos. m^{-2} and in Kayamkulam Estuary as 80±28 nos. m^{-2} (Ampili and Sreedhar, 2016). Sivashankar *et al*. (2015) studied the bivalve resources of Mulky Estuary, Karnataka and reported two clam species, *M. casta* and *P. malabarica* from this Estuary with an average density of 117 nos. m^{-2} and 46 nos. m^{-2} respectively. Laxmilatha *et al*. (2006 b) carried out a rapid survey to assess the bivalve resource and potential stock of Chettuva Estuary in Kerala and observed a clam biomass between 72 to 675 g m^{-2} which is lower than the observations in the present study. Nagvenkar *et al*. (2014) reported *P. malabarica* forms the most abundant and commercially important species in the estuaries of Mandovi (Chicalim) and Zuari (Nerul) with biomass of 8-25 g m^{-2} and 10-37 g m^{-2} respectively which is the lowest clam biomass observed from the Indian estuaries.

Species composition

Five species of clams were recorded from the Tuticorin Bay during the present study, among which, *M. casta* was the most dominant throughout the study period. Overall species composition during the study period was accounted by *M. casta* (33%), *G. pectinatum* (24%), *M. opima* (22%), *P. malabarica*, (21%) and *M. meretrix* (< 1%). At TB-1 four clam species were recorded and *G. pectimantum* was the major (32%) species followed by *M. casta* (30%), *M. opima* (23%) and *P. malabarica* (14%). At TB-2, among the five clam species recorded, *M. casta* (35 %) was most dominant species followed by *P. malabarica* (27%), *M. opima* (22%) and *G. pectinatum* (15%). *M. meretrix* was the least dominant species (1%) which was noticed only during the month of February and March. Similarly, TB-3 recorded five clam species in which *M. casta* was the dominant species (31%) followed by *G. pectinatum* (29%), *M. opima* (21%) and *P. malabarica* (19%). *M. meretix* was observed only during March and contributed 1% to the population at this station. In Pazhayakayal Estuary the clam resource was supported by a single species, *M. casta*. The clam species composition of Tuticorin Bay and Pazhayakayal Estuary is presented in Fig. 6.

Kripa *et al*. (2012), observed similar heterogeneous clam populations at Tuticorin Bay consisting of species like *M. meretrix, M. casta, Anadara granosa, M. opima, Donax cuneatus* and *P. malabariaca.* Dharmaraj *et al.* (2005) reported *Gafrarium tumidum* and *M. opima* exploitation from Tuticorin Bay. In Indian waters, high diverse clam populations have been reported by authors from different estuaries. Thangavelu and Sanjeevaraj (1988), reported *M. casta* and *M. opima* from Pulicat Lake. Lagade *et al.* (2013) recorded *M. casta, M. meretrix, M. opima, Paphia laterisulca* and *P. textile* from Bhatye Estuary, Maharastra. Gomathi *et al.* (2017)

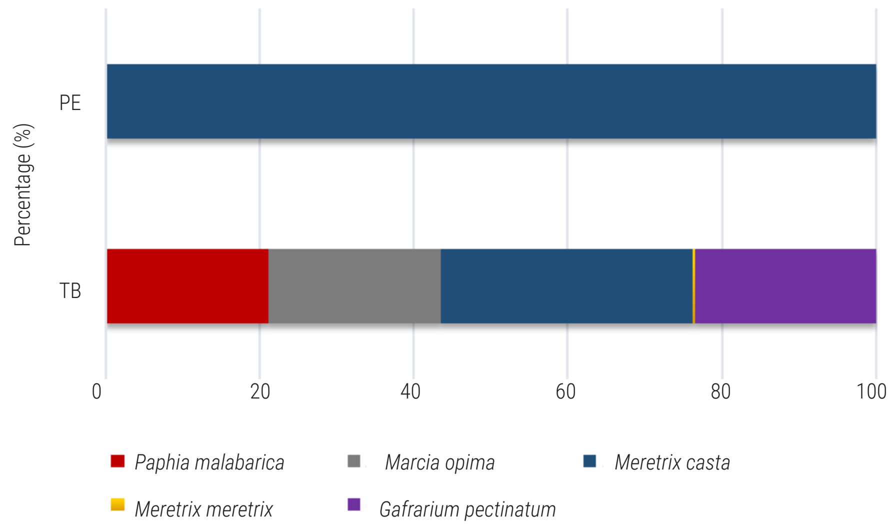

Fig. 6. Clam species composition in Tuticorin Bay and Pazhayakayal Estuary. PE: Pazhayakayal Estuary; TB: Tuticorin Bay

reported *Paphia malabarica, Marcia opima* and *Meretrix casta* from Muthalapozhi Estuary, Kerala. Ravindran *et al.* (2006) reported four clam species *V. cyprinoides, M. casta, P. malabarica* and *Sunetta scripta* from Vembanad Lake, Kerala. The dominance of black clam *V. cyprinoides* has been reported from Vembanad Lake, Kerala (Kurup *et al.*, 1990; Kripa *et al.*, 2004; Suja and Mohamed, 2010; Vijaya-Krishna and Ammini 2018). Thomas and Nasser (2009) reported the dominance of *P. malabarica* from Dharmadom Estuary, Kerala. Similar to Pazhayakayal Estuary, dominance of monospecific (*M. casta*) clam population were reported from Athankarai Estuary of Tamil Nadu (Rao *et al.*, 1987; Nayar *et al.*, 1988; Kavitha *et al.*, 2021).

M. casta species is found to be the dominant clam species in many estuarine waters like Chunnambar Estuary, Puducherry and Athankarai Estuary, Tamil Nadu (Kavitha *et al.*, 2021), Chaliyar and Kavvai, Kerala (Laxmilatha, 2013) and Chettuva Estuary (Laxmilatha *et al.*, 2006 b). The Moorad Estuary, Kerala has significant populations of *M. casta* and *M. meretrix* (Laxmilatha *et al.*, 2011). Parulekar *et al.* (1973) reported *M. casta* as the dominant species in Mandovi, Cumbarjua Canal and Zuari estuarine systems of Goa. Sivashankar *et al.* (2015) reported four species of clams (*M. casta, M. meretrix, P. malabarica* and *Donax* spp.) from the Mulki Estuary, Karnataka. *M. casta* forms a significant sustenance-level fishery in all major estuaries of India (Narasimham, 1991) due to its euryhaline nature, hence can tolerate low salinities and prefers high sand and silt habitats.

Principal component analysis (PCA)

As per the principal component analysis, the extracted PC1 and PC2 for Tuticorin Bay explained 71.30%, and 28.7 % of variation in physicochemical parameters with clam density and biomass, whereas in Pazhayakayal Estuary there were 64.1%, and 35.9% of variation. The correlation matrix loading of the significant principal components for the two locations are shown in Table 2. In Tuticorin Bay, the results of the PC1 revealed that atmospheric temperature, sea surface temperature, dissolved oxygen, NH_3, TSS,

Table 2. Eigenvalues, percentages of explained variance and correlation based principal component analysis (PCA) of physicochemical variables in Tuticorin Bay and Pazhayakayal Estuary

Physicochemical variables	Tuticorin Bay		Pazhayakayal Estuary	
	PC1	PC2	PC1	PC2
Water quality parameters				
Eigen values	20	8.05	17.9	10.1
%Variation	71.3	28.7	64.1	64.1
Cumulative% Variation	71.3	100	35.9	100
AT	-0.151	-0.26	0.236	0.002
SST	0.029	-0.35	0.17	-0.219
Salinity	-0.217	-0.086	-0.118	0.273
DO	0.215	-0.1	0.168	-0.222
GPP	-0.223	0.023	-0.236	-0.007
NPP	-0.223	0.026	-0.213	0.137
NH_3	-0.223	0.037	0.181	-0.202
TSS	0.224	0	-0.231	-0.066
TDS	0.224	-0.002	0.226	0.092
Total Chlorophyll	-0.219	0.07	0.234	0.038
NO_2	-0.066	-0.337	-0.096	-0.288
PO_4	-0.132	-0.284	-0.106	-0.282
SiO_3	0.193	0.178	0.08	-0.297
NO_3	-0.212	0.112	-0.021	-0.314
BOD	-0.104	0.312	-0.228	0.08
Total alkalinity	-0.076	-0.331	-0.19	-0.187
Clay (%)	0.122	-0.295	-0.212	-0.139
Sediment parameters				
Silt (%)	0.008	0.352	-0.153	-0.24
Fine sand (%)	0.172	0.225	0.143	-0.251
Coarse sand (%)	-0.197	-0.167	-0.216	-0.128
Organic carbon	0.219	-0.073	-0.182	-0.2
Organic matter	0.219	-0.072	-0.182	-0.202
N_2	0.218	-0.079	-0.215	-0.13
Clam density	-0.221	0.059	-0.228	0.081
Clam biomass	-0.221	0.057	-0.23	0.07

TDS, NO_2, PO_4, SiO_3, BOD, clay (%), silt (%), fine sand (%), organic carbon, organic matter and N_2 are positively influencing the clam density. The variables, like salinity, GPP, NPP, chlorophyll, NO_3, total alkalinity, coarse sand (%), clam density and biomass are negatively impacting clam density explained by 71.3% of the total variance along the first principal axis. In Pazhayakayal Estuary, the result of the PC1 revealed that atmospheric temperature, sea surface temperature, dissolved oxygen, NH_3, TDS, Chlorophyll, SiO_3 and fine sand (%) are positively influencing the clam density and biomass. The variables, like salinity, GPP, NPP, TSS, pH, NO_2, PO_4, BOD, total alkalinity, clay (%), silt (%), coarse sand (%), organic carbon, organic matter, and N_2 are negatively impacting and explained by 64.1% of the total variance along the first principal axis.

The present study demonstrated clear ecosystem-wise variations in both physicochemical variables and clam population characteristics. Similarly, significant differences were observed in clam density and species diversity between Tuticorin Bay and Pazhayakayal Estuary, largely influenced by environmental factors such as dissolved oxygen, salinity, soil texture and organic content. The clam population in Pazhayakayal Estuary was characterised by high density and low species diversity with a predominantly monospecific assemblage. In contrast, Tuticorin Bay supported multispecies populations with comapratively lower densities. the fine sandy bottom with high organic carbon content in Tuticorin Bay appear to favour greater species diversity, wheras the coarser sandy bottom and hyposaline conditions in Pazhyakayal Estuary support high population density and but lower diversity. These findings highlight the critical role of physicochemical factors in shaping both population density and species diversity of clams across different habitats.

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