

Factors controlling organic matter composition and trophic state in seven tropical estuaries along the west coast of India

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Abstract

To understand the organic matter (OM) sources and trophic states, spatial and seasonal (post-monsoon and pre-monsoon) variation in sedimentary OM compositions was investigated in seven tropical estuaries of the state of Maharashtra along the central west coast of India. Based on the result of cluster analysis estuaries were segregated into two distinct groups; Northern Maharashtra (NM) and Southern Maharashtra (SM) owing to dissimilarity in OM characteristics potentially constrained by geomorphology and catchment properties. Enrichment of C_{org} and major biochemical compounds (lipids, carbohydrates and proteins) in the middle zone of most estuaries highlighted towards the addition of allochthonous OM. Results of Principal Component Analysis (PCA) highlighted the similar source of OM in most of the estuaries during both seasons and their distribution largely constrained by grain size change. The benthic trophic state indicated the prevalence of eutrophic state in the middle zone of the investigated estuaries, which may be sporadic and dependent upon anthropogenic activities in the study area.

Keywords: west coast of India. tropical estuaries. organic carbon. biochemical compounds. trophic state.

1. Introduction

Characteristics of organic matter (OM) present in estuarine sediment provide important information, which is essential for understanding the processes influencing estuarine benthic biological community structure, their productivity and overall benthic ecosystem function (Dell'Anno et al. 2002; Pusceddu et al. 2009, 2011; Venturini et al. 2012). Estuaries are a place of mixing between rivers and the coasts/ocean, act as a major burial site for OM supplied from riverine, coastal and marine sources. A significant fraction of river-borne OM mainly generated from the terrestrial vascular plant, soil and anthropogenic activities such as domestic sewage and industrial effluents are eventually buried into the estuarine sediment. The nature of OM present in estuarine sediment often indicates about their bio-availability and/or further role in nearshore biogeochemical processes. Chemical stability, biochemical compositions, and interaction with clay minerals are the factors largely respond to sedimentary OM degradation in the estuarine environment. Generally, a labile fraction of OM (lipids, proteins, and carbohydrates) consumed by bacteria and preferentially oxidized often prior to their deposition in surface sediment (Ittekkot and Laane 1991; Colombo et al. 1996; Venturini et al. 2012; Kumar et al. 2013). The non-labile fraction, also termed as Complex Organic Matter (COM), which mainly includes humic and fulvic acids degrade at a slower rate, thereby utilized in the benthic food web (Fichez, 1991; Middleburg et al. 1999; Danovaro et al. 1999). In order to understand the mechanism of potential OM degradation as well as to differentiate between labile and non-labile fraction of it, concentrations and ratios of biochemical compounds have been widely used in estuarine and marine studies reported elsewhere (e.g. Cowie and Hedges, 1992; Fabiano and Danovaro, 1994; Danovaro et al. 1999; Pusceddu et al. 1999, 2003; Civitanes et al. 2002; Kumar et al. 2013; Gireeshkumar. 2013; Salas et al. 2015).

The fundamental links among changing global condition, aquatic ecosystem functioning and human health are complex as they are incidental, change in a space and time scale, and frequently interfered by natural climate change (varying precipitation), and anthropogenic activities (land-use modification) in the tropic. Estuaries located along the tropical west coast of India, annually receive a disproportionate amount of precipitation during south-west monsoon as well as non-monsoon period owing to regional climate variability and global climate change (Prakash et al. 2015). Anthropogenic activities such as the existence of numerous dams on the rivers of tropical India, significantly influenced the quantitative sediment and OM transport through the estuaries (Panda et al. 2011; Gupta et al. 2012). The nature of riverine OM across the estuaries of the west coast of India intricately corresponds to a land-use change in the region questioning their further role in nearshore

biogeochemical processes as a paradox (Pradhan et al. 2014). Our understanding on the qualitative capacity of OM and their availability as a food source for benthic biological community, by analysing elemental and biochemical compounds data will add great values across these estuaries, and will help to assess the existing trophic status.

Sedimentary biochemical properties present in a suite of seven tropical estuaries across latitudinal gradient (south-north) of the west coast of India is reported in this study, with a hypothesis about the strong influence of natural and anthropogenic activities on the distribution of OM characteristics. Selected seven estuaries to cover the coastal region of the state of Maharashtra, which is considered as the economic strength of India and located along the Eastern Arabian Sea. The coastal stretch of this province is one of the highly urbanized regions in India and thus these estuaries receive a large amount of domestic and industrial wastes beside the natural river runoff that occurs during south-west monsoon period (i.e. June to September in a year). The prime objectives of this study are (i) to delineate spatial and seasonal changes in sedimentary OM composition in seven tropical estuaries of the west coast of India and (ii) to identify the factors controlling changes in sedimentary OM and trophic state in these estuaries. The collective results on spatial as well as seasonal changes in sedimentary biochemical properties measured in a suite of seven tropical estuaries in this study will provide baseline information about OM cycling in urbanized estuaries of India and comparison with other tropical regions of the world.

2. Materials and method

2.1. Study area description

The state of Maharashtra located below the tropic of cancer has a geographical area of 0.3×10^6 km², which is roughly 9% of the total geographical area of India. The population density of the state is 372 inhabitants km⁻² and nearly similar to the population density of India (399 inhabitants km⁻²; Census India, 2015). Nearly thirty small rivers, with catchment area $\geq 10^3$ Km², mainly flooded during the southwest monsoon rainfall are annually flowing from the Western Ghats mountain ranges and debouching into the Eastern Arabian Sea. Together these rivers occupy an area of 27×10^3 km², with a net water flow of 53.3×10^9 m³ yr⁻¹, which roughly equals to 10% of the total geographical area of Maharashtra and 20% of the total annual riverine flow into the Arabian Sea respectively. Among them the rivers named Ulhas (3084 km²), Patalganga (940 km²), Amba (740 km²), Kundalika (825 km²), Savitri (2889 km²), Vashishti (2238 km²) and Shastri (2174 km²), investigated in this study cover about 50% of the total river flowing from the state of Maharashtra and contributes to 56% of the total riverine flow of west flowing rivers of Maharashtra. Unlike the

large rivers such as Narmada and Tapi in the north, the west flowing small rivers are relatively steeper and the average lengths to elevation (L/H) ratio of studied rivers vary between 0.05 and 0.2. Climatologically, the temperature along these river basins vary between 26°C and 32°C, with maximum temperature occur during May (pre-monsoon). The average precipitation across the studied river systems is 3322 mm yr⁻¹, which is much higher than the average precipitation of state of Maharashtra i.e. 733 mm yr⁻¹ (Sharad et al. 2007). Anthropogenic activities such as the discharge of industrial and domestic waste are predominant across these rivers and all along the coastal Maharashtra rivers. The ratio between the amount of industrial and domestic waste draining into the studied rivers vary between 0.17 to 1.88, with higher in Amba estuary and lower in Ulhas indicated that the former is dominantly receives industrial wastes and the latter is affected due to large human population across the basin (Table. 1). The studied estuaries are governed by tides and coastal currents predominantly semidiurnal with a diurnal inequality. The tidal ranges vary between 0.2 and 5.2 m, with roughly increased from Shastri in the south to Ulhas in the north. The coastal currents are clockwise or shoreward during February-September, anticlockwise during November-January and transitional in October (CSIR-National Institute of Oceanography, Technical report. 2009).2.2.

Sampling and pre-treatment

Fifty-five surficial sediment samples were collected across the salinity gradient in all seven river-estuary systems namely (Ulhas (US), Patalganga (PT), Amba (AB), Kundalika (KK), Savitri (ST), Vashishti (VT) and Shastri (ST)). About five to ten samples from an estuary were collected during post-monsoon (November-December, 2015) as well as pre-monsoon (March-April, 2016) seasons in this study (Table.1). The samples collected are representative of upper, middle and lower part of estuaries as well as the near shore (in sea, 5 km from shore) region. The sediments collected using a Van-Veen grab (40×40cm) were stored at -4 °C until analysis. All the sediments were freeze-dried and homogeneously grinded prior to elemental and biochemical measurements.

2.3. Grain size analysis

Sediment grain size analysis was performed using wet sieving method as described in Buchanan, (1984). Briefly, 25g of freeze dried sediment was dispersed in 200 ml of deionized water then added with 10 ml Sodium hexametaphosphate [(NaPO₃)₆] stirred and allowed to stand overnight in a glass beaker. The solution was sieved through 63 μm sieve and dispersed in deionized water. The sediment fractions extracted were dried and weighed for respective percentages of silt and clay, with a measurement error of ≤1% in the entire dataset.

2.4. Chemical analysis

The weight percentage of total organic carbon (C_{org}) and total nitrogen (N_{tot}) was measured using an elemental analyser (CHNS; Vario EL Cube) at CSIR-National Institute of Oceanography, Regional Centre Mumbai. Briefly, 10mg of sediment used for the analysis of inorganic carbon using an Elementar HANAU, TC/TIC solid module analyser (Germany). The content of C_{org} was obtained by subtracting inorganic carbon from the total carbon values. Repetitive measurement (at least ten times) of few sediment samples were carried out at the certain interval during the analysis to evaluate the system performance. Throughout this study, average precision for C_{org} and N_{tot} is calculated as $\pm 5\%$ of the data value.

Biochemical constituents were analysed by using a UV-Visible spectrophotometer (SHIMADZU Co.). Total carbohydrates (CHO) were analysed following phenol-sulphuric acid method (Dubois et al. 1956) and expressed as glucose equivalents. For the extraction of total protein (PRT), sediment was digested in 1N Sodium Hydroxide (NaOH) by heating in a water bath. The slurry was centrifuged, and an aliquot of the clear supernatant was used for estimation of PRT using Folin phenol reagents (Lowry et al. 1951). PRT concentrations are given as Bovine Serum Albumin (BSA) equivalents. Total lipids (LPD) were extracted from sediment samples by direct elution with chloroform and methanol (Bligh and Dyer, 1959), estimated using sulphophosphovanillin method (Barnes and Blackstock, 1973), and expressed as cholesterol equivalents. Concentrations of CHO, PRT, and LPD were converted to carbon equivalents by using the following conversion factors: 0.40, 0.49 and 0.75 g of C/g, respectively (Fabiano and Danovaro, 1994). The sum of CHO, PRT and LPD carbon (hereinafter referred as Bio Polymeric Carbon (BPC); Fichez, 1991; Fabiano et al. 1995), which equals to the net amount of carbon available to the benthic consumers. The residual and uncharacterized fraction of the Corg (hereinafter termed as COM; Fichez, 1991) calculated is the difference between Corg and BPC. The relative percentage of BPC as Corg (BPC/C_{org}) was further used to assess the food index and trophic status of coastal marine systems (Dell'Anno et al. 2002; Pusceddu et al. 2003; 2009). Moreover, this is accomplished with the use of biochemical indices like concentrations and ratios of CHO, PRT and LPD (e.g. PRT/CHO and LPD/CHO) (Fabiano et al. 1997; Grémare et al. 2002; Dell'Anno et al. 2002). The precision of the method was $\pm 5\%$. All the analyses were carried out in triplicate and the average is reported.

2.5. Statistical analysis

The statistical significance (95% confidence interval) of differences in elemental and biochemical parameters observed in sediments was tested using a standard one-way analysis of

variance (ANOVA). Cluster analysis was performed to explore the relationship between different estuaries. Pearson's correlation coefficient was used to test the correlation between grain size, elemental and biochemical parameters and two-tailed p values were calculated. Prior to the Principal Component Analysis (PCA), normalization of the data was done and Eigenvalue greater than 1 was considered for identifying the principal components (e.g. Pradhan et al. 2014). Parameters such as C_{org} and N_{tot} were used to infer the OM quality, whereas CHO, PRT, and LPD were used to consider the bioavailability. The grain size parameters such as sand, silt, and clay contents were used to infer hydrodynamic conditions that affect the sediment compositions during the study period. All statistical analyses were performed using SPSS 10.0 and results were plotted using Grapher 4.0.

3. Results and discussion

The seven estuaries of this study broadly categorised in two groups named NM (Northern Maharashtra) and SM (Southern Maharashtra), based on the results obtained from hierarchical cluster analysis performed on sedimentary organic biochemical parameters (C_{org} , N_{tot} , CHO, PRT, and LPD). The clustering pattern of these two grouped estuaries closely follows distinct geographical and geomorphological characteristics between low locations along the west coast of India (Fig. 2).

The study of grain size parameters often reveal information about the interaction between hydrodynamic condition and sediment distribution as well as their path ways in river-estuary environment (Venkatramanan et al. 2011). Hydrodynamic sorting of sediment owing to tidal and wave action in estuarine region holds strong control on the dispersal patterns of sediment as well as associated chemical constituents. In this study, sediment grain size distribution indicated higher sand content in estuaries of SM group (avg. $45.8 \pm 4.3\%$ in post-monsoon and $59.9 \pm 7.9\%$ in pre-monsoon) than the estuaries of NM group (av. $37.1 \pm 8.8\%$ in post-monsoon and $31.6 \pm 17.0\%$ in pre-monsoon). Sediments from both the estuary groups were dominated with silt, with an average silt content of $41.7 \pm 12.0\%$ in post-monsoon and $42.6 \pm 14.2\%$ in pre-monsoon in NM estuaries and $33.1 \pm 5.7\%$ in post-monsoon and $52.0 \pm 7.1\%$ in pre-monsoon in SM estuaries (Fig. 3). Estuaries in both the group have lower clay content as compared to the sand (NM estuaries: $18.0 \pm 5.1\%$ in post-monsoon and $25.8 \pm 3.2\%$ in pre-monsoon; SM estuaries: $10.2 \pm 4.2\%$ in post- monsoon and $7.0 \pm 2.7\%$ in pre-monsoon). Overall, the significant variations (spatial and seasonal) in sand, silt and clay contents were noticed in all the estuaries of SM group as compared to the NM group. The changes in the distribution of sediment grain size across the NM and SM group estuaries presumably have close resemblance with the differences in the magnitude of their river water discharge (Table.1; Pradhan et al. 2014). Fine sediments get easily transported during heavy river runoff in monsoon, leaving

behind the coarser sediments during pre-monsoon and post-monsoon seasons. Moreover, such sorting process during hydrodynamic condition such as tidal action in the estuaries can not be ruled out in this study (Bianchi et al. 2007).

3.1. Elemental composition of sedimentary OM

The C_{org} contents varied between 0.2 and 4.0% during post-monsoon, whereas from 0.1 to 4.2% during pre-monsoon season, indicating no significant seasonal differences between OM quality or bioavailability in all the estuaries of this study (Fig. 4). Overall, the mean C_{org} contents were higher in NM estuaries ($2.2\pm 0.8\%$; post-monsoon and $2.0\pm 0.7\%$; pre-monsoon) as compared with SM estuaries ($1.5\pm 1.1\%$; post-monsoon and $1.3\pm 1.0\%$; pre-monsoon). The contents of C_{org} observed during this study are comparable with C_{org} contents found in other tropical small estuaries along the west coast of India (Martin et al. 2011; Gireeshkumar et al. 2012; Pradhan et al. 2014) and other regions of the world (Datta et al. 1999; Liu et al. 2006; Cotano and Villate 2006). The spatial distribution of C_{org} indicated higher values in the middle estuary, which is roughly two times higher than the average value obtained during post-monsoon and one time higher than the average value obtained during pre-monsoon in most estuaries except the SR (SM group). On average, the sedimentary C_{org} contents increased from the south through the north in the studied estuaries during both the seasons. The overall range of N_{tot} in sediment varied from 0.02 to 0.35% during post-monsoon and from 0.01 to 0.28% during pre-monsoon in all the estuaries. Mean N_{tot} contents were similar in NM estuaries ($0.1\pm 0.05\%$) as well as SM estuaries ($0.1\pm 0.05\%$) during this study indicating their common origin in these estuaries. Like C_{org}, the distribution of N_{tot} also showed higher values in the middle zone of the estuaries during both seasons, indicating accumulation of OM in that region. The spatial distribution of C_{org}, as well as N_{tot} contents, were statistically significant ($p\leq 0.001$; ANOVA) in most of the estuaries during all seasons (Fig. 4). However, the C_{org} and N_{tot} did not indicate any significant seasonal difference during the entire study period. Apparently, higher C_{org} appeared to be closely associated with higher anthropogenic inputs (industrial as well as domestic) in NM estuaries as compared to SM estuaries (Table. 1). C_{org} exhibited a significant positive correlation with silt (Pearson's $r = 0.49$; $p\leq 0.05$) and a negative relationship with sand (Pearson's $r = -0.54$; $p\leq 0.05$) in NM estuaries (Table. 2), whereas the C_{org} showed significant positive relationship with clay (Pearson's $r = 0.39$; $p\leq 0.05$) and silt (Pearson's $r = 0.64$; $p\leq 0.05$) and a negative relationship with that of sand (Pearson's $r = -0.66$; $p\leq 0.05$) in the SM estuaries (Table. 2). Overall, the sediment grain size holds significant control on the C_{org} content in both NM and SM estuaries, which may be attributed to the relatively high absorptive capacity of fine particles for OM

and higher settling rates of sediments (Cotano and Villate 2006). The range of Corg/Ntot ratios in sediment varied from 8.8 to 33.8 during post-monsoon and from 7.9 to 30.0 during pre-monsoon in all the estuaries (Table. 3). Mean Corg/Ntot ratios were higher in NM estuaries (20.0 ± 6.3 ; post-monsoon and 16.9 ± 5.7 ; pre-monsoon) as compared to that in SM estuaries (15.1 ± 6.4 ; post-monsoon and 15.2 ± 5.3 ; pre-monsoon), also Corg/Ntot was higher in middle reaches of most estuaries. Overall, the distribution of Corg/Ntot in sediment were statistically significant ($p \leq 0.05$; ANOVA) during both the seasons in estuaries such as PT (NM group) and KK and ST (SM group). The Corg/Ntot ratios of sediments in studied estuaries are compared with Corg/Ntot ratio reported for other estuaries in World (Table 4). The observed Corg/Ntot range has close proximity with Corg/Ntot of OM sources such as plants and soils along the west coast of India (Pradhan et al. 2014). The values are nearly similar when compared with Corg/Ntot reported for Yangtze estuary and estuaries along east coast of India, indicating mixing inputs of terrigenous and marine materials obviously modified by organic matter diagenesis and biological processing (Liu et al. 2006). The smaller river-estuary system studied here apparently receive enhanced allochthonous OM, mainly mixed sources of plants and soils in the sediment delivered to the estuary during the high water flow condition.

3.2. Biochemical composition of sedimentary OM

The CHO concentrations were between 1.0 and 5.9 mg/g during post-monsoon, whereas from 1.1 to 4.9 mg/g during pre-monsoon season in all the estuaries of this study (Fig. 4). Mean CHO contents were roughly higher in NM estuaries (3.1 ± 0.9 mg/g; post-monsoon and 3.0 ± 0.7 mg/g; pre-monsoon) than the SM estuaries (2.3 ± 0.7 mg/g; post-monsoon and 2.1 ± 0.6 mg/g; pre-monsoon). The spatial distribution of CHO indicated higher values in middle estuary, which is roughly one time higher than the mean value during post-monsoon except AB (NM group) and during pre-monsoon in most estuaries except the SR (SM group). The spatial distribution of CHO content was not statistically significant in most of the estuaries during all seasons, except the ST (SM group; $p \leq 0.05$; ANOVA).

Exceptionally, higher CHO (5.9 mg/g) was noticed in the middle zone of the PT Estuary in NM group during post-monsoon seasons of this study. On an average, the sedimentary C_{org} contents increased from the south through the north in the studied estuaries during both the seasons. The CHO concentrations observed in this study were consistent with the values previously reported elsewhere e.g. western coastal Bay of Bengal (CHO=2.8–4.7 mg/g; Kumar et al. 2013), and Cochin Estuary, the central west coast of India (CHO=1.28–4.43 mg/g; Jacob et al. 2008). Moreover, the observed CHO in this study were comparable with other regions of globe e.g. San Diego trough (CHO= 0.9 mg/g;

Degens et al. 1963), Baltic Sea (CHO=0.5–3.5 mg/g; Naik and Poutanen 1984) and Santa Barbara Basin, California (CHO=2.2 mg/g; Prashnowsky et al. 1961) (Table. 4). The lowest concentration of CHO (1.0 mg/g) was found in the upper zone of the KK Estuary in NM group during post-monsoon season. Overall, the CHO concentrations were higher in the NM than SM grouped estuaries and their distribution across the longitudinal cross-section of the estuary was significant ($p < 0.001$; ANOVA) during the study period. The higher concentrations of sedimentary CHO in the middle zone of estuaries during both the seasons were attributed to detrital nature of OM resulted during addition and removal processes of OM as well as disproportionate degradation of proteins over carbohydrate conducive to natural and anthropogenic activities (Joseph et al. 2008; Venturini et al. 2012).

Concentrations of PRT were ranged between 0.03 and 2.3 mg/g during post-monsoon, whereas from 0.02 to 2.3 mg/g during pre-monsoon season in all the estuaries of this study (Fig. 5). Average PRT concentration was roughly lower in the NM estuaries (0.7 ± 0.5 mg/g; post-monsoon and 0.8 ± 0.6 mg/g; pre-monsoon) as compared to the SM estuaries (0.7 ± 0.6 mg/g; post-monsoon and 0.6 ± 0.5 mg/g; pre-monsoon). Exceptionally higher value of PRT was found in the lower regions of the SR Estuary (SM group). The ranges of PRT found during this study are comparable with other studies around the world (Table. 4). The spatial distribution of PRT indicated higher values in the middle zone of most of the estuaries except the SR (SM group) during both the seasons. The spatial distribution of sedimentary PRT was not significant ($p \geq 0.05$; ANOVA) in most of the studied estuaries and during both the seasons. Furthermore, the PRT concentrations did not indicate any specific trend of variation from the south through the north in the study area. The exceptionally higher PRT found in the lower reaches of the SR Estuary can be attributed to anthropogenic source of OM such as fishery wastes generated from localized fishing activities and situated on the banks of area release waste materials into the estuary contributing OM enriched with PRT, which is ultimately adsorbed/settled in the sediment phase (Balasubramanian et al. 2012).

The LPD contents were varied between 0.2 and 8.5 mg/g during post-monsoon and from 0.2 to 9.7 mg/g during pre-monsoon in all the estuaries of this study (Fig. 5). Mean LPD contents were roughly higher in NM estuaries (4.8 ± 1.2 mg/g; post-monsoon and 4.8 ± 1.9 mg/g; pre-monsoon) than the SM estuaries (1.9 ± 1.2 mg/g; post-monsoon and 1.5 ± 0.9 mg/g; pre-monsoon) in this study. The observed sedimentary LPD concentrations in this study are roughly higher than other regions of the world e.g. Mundaka Estuary, Spain (LPD= 0.3–5.0 mg/g; Cotano and Villate 2006), Rio de la Plata estuary, Uruguay (LPD= 0.5–8.4 mg/g; Venturini et al. 2012) (Table 4). The spatial distribution of LPD was statistically significant ($p \leq 0.001$; ANOVA) in most of the estuaries and indicated higher

values in middle estuary, which is roughly one times higher than the mean value during post-monsoon and pre-monsoon in most estuaries except the SR (SM group). On average, the sedimentary LPD concentrations were increased from the south through the north in the studied estuaries, which is due to the increased anthropogenic load in the north compared to the south estuaries. The higher levels of LPD found in the middle zone of most of the estuaries was in line with enriched C_{org} , N_{tot} CHO and PRT obviously modified by organic matter diagenesis and biological processing and accumulated in the middle zone of studied estuaries.

The BPC contents were varied between 0.6 and 9.4 mgC/g during post-monsoon, whereas from 0.7 to 10.2 mgC/g during pre-monsoon season in all the estuaries of this study (Fig. 5). Mean BPC contents (i.e. the amount of carbon available to benthic organisms) were higher in NM estuaries (5.2 ± 1.3 mgC/g; post-monsoon and 5.2 ± 1.8 mgC/g; pre-monsoon) as compared to the SM estuaries (2.6 ± 1.3 mgC/g; post-monsoon and 2.3 ± 1.1 mgC/g; pre-monsoon). Tenore and Hanson (1980) suggested that about 5–15% of sedimentary detritus, depending upon the environmental characteristics is generally available at any time for benthic consumers. The spatial distribution of BPC indicated higher values (higher than the seasonal average) in the middle zone of most of the estuaries except the SR (SM group). The spatial distribution of BPC content was statistically significant ($p \leq 0.001$) in most of the estuaries during all seasons. The relative percentage of average CHO, PRT and LPD contents in BPC was 35.5%, 8.7% and 55.8% in NM group estuaries. Whereas the percentage of CHO, PRT and LPD contents in BPC was 48.5%, 14.3% and 74.5% in SM group estuaries. Collectively it indicates higher degradation of PRT in the sediments of most estuaries during the study period. Moreover, the COM contents were varied between 1.4 and 33.4 mg/g during post-monsoon, whereas it varied between 0.2 and 34.6 mg/g during pre-monsoon season in all the estuaries of this study. Mean COM contents were higher in NM estuaries (16.6 ± 8.0 mg/g; post-monsoon and 15.1 ± 7.3 mg/g; pre-monsoon) as compared to the SM estuaries (12.5 ± 9.3 mg/g; post-monsoon and 11.5 ± 8.8 mg/g; pre-monsoon).

3.3. Changes in quality of sedimentary OM

Changes in the BPC contribution to C_{org} resulted in this study, owing to the changes in LPD concentrations. Furthermore, BPC vs. C_{org} showed the positive relationship (Pearson's $r = 0.73, 0.81$; $P < 0.001$) in both NM and SM grouped estuaries. The distribution of COM was in line with C_{org} during both seasons of this study in both groups of estuaries. Higher value of COM recorded in NM estuaries (~ 16.0 mg/g) coincided with higher C_{org}/N_{tot} (>15), indicative of mixing inputs of terrigenous and marine OM modified by diagenesis and biological processing, which eventually

buried into the sediments from the water column (Zavattarelli, 1986; Metzler and Smock, 1990). Our data also support the hypothesis that COM display conservative behavior in estuaries (Ittekkot 1988; Spitzzy and Ittekkot 1991). Decomposition and burial of terrigenous material ($C_{org}/N_{tot} > 10$; Hargrave et al. 1995) might have also contributed to higher COM concentration. The ratio BPC/ C_{org} is used as an indicator to identify the quality of OM potentially bioavailable to the consumers (Danovaro and Fabiano 1997). The contribution of C_{org} to BPC was higher in NM grouped estuaries (BPC/ C_{org} = 24.8%) as compared to the SM grouped estuaries (BPC/ C_{org} = 17.9%) during both the seasons of this study. Also, the C_{org}/N_{tot} ratio showed an inverse relationship with BPC/ C_{org} (Table. 2) in SM grouped estuaries. Collectively, this indicated that the OM in surface sediments of the SM grouped estuaries is potentially less bioavailable and/or composed of refractory material than that in NM grouped estuaries (e.g. Fabiano et al. 1995).

The ratio of LPD/CHO is used to describe the OM quality in sediments (Fabiano and Pusceddu 1998; Gremare et al. 2002). In addition, higher LPD concentrations indicate healthy benthic trophic status (Danovaro et al. 1999, 2000; Dell' Anno et al. 2002). The LPD/CHO ratios (0.1 to 2.8) in this study were comparable with previous studies in smaller tropical estuaries Joseph et al. 2008 (Range; 1.02 to 4.74); Renjith et al. 2012 (Range; 0.04 to 1.36). A higher value of LPD/CHO (2.8) was found at the lower part of the AB Estuary (NM group) during pre-monsoon, presumably resulted due to high nutritional value as well as the fishing activities in the area. The lower values of LPD/CHO (0.2) were found at upper and lower part of the VT Estuary, upper and middle part of the SR Estuary (SM group) during post-monsoon. Overall, the higher values of LPD/CHO in NM grouped estuaries are indicative of high biological productivity, whereas the OM in SM grouped estuaries is likely sourced from allochthonous sources (Jacob et al. 2008).

The PRT/CHO ratio is widely used as an indicator for the source of OM as well as their potential age in aquatic sediment (e.g. Danovaro et al. 1993; Fabiano et al. 1995; Pusceddu et al. 1999; Cividanes et al. 2002). Higher PRT/CHO ratio often indicates relatively fresh nature of OM in estuarine and marine sediment. In this study, the PRT/CHO was varied between 0.01 and 1.3 during both the seasons (Table. 3), with maximum value was at lower part of the SR Estuary (SM group). Relatively lower values of PRT/CHO ratio in most of the studied estuaries indicated the presence of aged OM and the role of protein as a potential limiting factor for the benthic consumers. Such condition may also arise due to disproportionate degradation of OM in these estuaries owing to the strong hydrodynamic condition. Generally, the PRT/CHO ratio ranges from ≥ 0.1 in sediments from oligotrophic deep-sea (500–2400m depth; Eastern Mediterranean Sea; Danovaro et al. 1993) to ≤ 10

in sediments from the coastal Antarctic region (Pusceddu et al. 1999). Collectively, the mean PRT/CHO ratio was ≤ 1 in this study, which indicated the presence of significant amount of allochthonous OM with relatively higher CHO content in these estuaries.

3.4. Principal Component Analysis (PCA)

Based on the result of PCA analysis, two dominant factors together explaining 76.5% and 74.0% of total 100% variance in the data set during pre-monsoon and post-monsoon seasons respectively controls OM quality during both the seasons (Fig. 6). The C_{org} and N_{tot} were closely associated with each other fall in positive quadrant along with other biochemical parameters PRT, CHO, LPD, and BPC as well as clay content. This indicated that origin and distribution pattern of OM in estuaries were mainly affected by clay content in sediment. Such condition was predominant in NM grouped estuaries due to higher clay content as compared to the SM estuaries. The SM group estuaries were within close proximity of sand and silt, which indicated that the sedimentary OM distributions in these estuaries are significantly influenced by physical processes during both the seasons. One of the important reasons for this phenomenon could be the geomorphological influence on sedimentary grain size and associated OM. The SM grouped estuaries have lower L/H ratio, thus have steeper slope as compared to the NM estuaries (Table 1). The steeper slope of basin helps rapid transport of sediment to the estuarine end during monsoon period, and hydrodynamic sorting at the estuarine end allowing the finer particle to transport along with water (Bianchi, 2007; Pradhan et al. 2014). The proximity of CHO with sand content in the opposite quadrant during post-monsoon could explain association of CHO with coarser particles, dominantly in SM grouped estuaries. This could be either due to simple sorting of sediment that are rich with CHO (fresh), or OM degraded with PRT and LPD, with left out CHO (degraded). Since, CHO stands out separately from other biochemical compounds signifying different preservation in sediment or apparently less degraded. Disproportionate degradation of PRT as well as LPD from different OM sources might have also resulted addition and removal of CHO in sediment in this study.

3.5. Benthic trophic status of the study area

The characterization of trophic state in estuarine ecosystem will highlight the complex linkage between biogeochemical constituents and existing food web. The seven important estuaries of this study have pedagogical potential to be a model for future sustainable development in estuarine ecosystems of this country. The estuaries experience multifarious anthropogenic activities such as under-treated industrial and sewage discharge from industries and population setups. Direct and indirect water discharges of fertilizer derived nutrient rich water could also be an important

nonpoint pollution source in these estuaries. The dominance of domestic vs. industrial wastes in these seven estuaries is different, which will significantly affect the coastal-adjacent region (Table.1). Therefore, understanding of trophic states in these estuaries will provide baseline information towards their potential for future environmental and societal characteristics due to economic development. In general, the trophic state can be categorized as oligotrophic (unproductive), mesotrophic (intermediate productivity) and eutrophic (highly productive). Anthropogenic activities such as input of untreated and OM rich sewage with higher nutrients often affect the benthic food due to alteration in the trophic state (e.g. Danovaro et al. 1999; Smith, 2003; Dodds and Cole, 2007). In this study, we assess the trophic state of seven tropical estuaries along the west coast of India based on BPC concentrations normalized to C_{org} as described in Pusceddu et al. 2011. The trophic state categories can be defined as; eutrophic (BPC= 3 mg C/g; algal fraction <12 % of BPC), mesotrophic (BPC = 1–3 mg C/g; algal fraction = 12–25 % of BPC) and oligotrophic (BPC <1 mg C/g; algal fraction >25 % of BPC).

In this study, according to Pusceddu et al. (2011) our results indicated that eutrophic state (BPC>3 mg C/g) prevailed in the middle zone of the most of the studied estuaries during both the seasons (Table. 5). Exceptional is to VT and SR, which showed a relatively mesotrophic state (BPC = 1–3 mg C/g) in their middle zone mainly during pre-monsoon season. The eutrophic state of the middle zone of the estuaries is likely due to the accumulation of large amounts of C_{org} with low degradation rate and associated refractory compounds (Danovaro et al. 1999). Furthermore, mixing of allochthonous OM from the hinterland sources have caused the variances in the trophic state among eutrophic, mesotrophic and oligotrophic (e.g. Thottathil et al. 2008; Pusceddu et al. 2009; Martin et al. 2011). Such variances and/or shifting in the trophic state may be sporadic and dependent upon natural and anthropogenic activities prevailing in the estuarine environment.

4. Conclusion

The biochemical signatures of OM indicating their bioavailability as a food source to the benthic biological community in the estuarine ecosystem is an important aspect of ecosystem functioning and human health. In this study, the comprehensive result on elemental as well as biochemical characteristics of sedimentary OM in seven tropical estuaries of the west coast of India along the eastern Arabian Sea has helped us to infer their composition and sources during post-monsoon and pre-monsoon seasons. Results from hierarchical cluster analysis segregated estuaries into two distinct groups; south Maharashtra (SM) and north Maharashtra (NM), alongside their latitude due to the significant dissimilarity of sedimentary OM properties in two groups. Such

property highlight towards difference in source control of OM in tropical estuaries, which may largely be constrained due to geomorphology and catchment properties. Enrichment of the sedimentary C_{org} and biochemical compounds in the middle zone of most of the studied estuaries indicated the addition of previously degraded allochthonous OM during both the seasons. Results of PCA analysis highlighted the unique source of sedimentary OM during both the seasons, with their characteristics varied due to grain size variance. The trophic state indicated the prevalence of eutrophic state in the middle zone of most estuaries during both seasons owing to excessive anthropogenic activities. The results of changing trophic state in studied seven important monsoonal estuaries of the central west coast of India underscore the necessity of further investigation in a seasonal as well as temporal scale to understand the potential impacts on the benthic community better. Furthermore, this study also describes the use of biochemical compounds composition alongside the sediment OM, as a tool for classifying the benthic trophic state, however, the threshold levels of biochemical compounds that describe trophic state and the response of benthic community towards the state may vary in tropic vs. non-tropical region needs further investigation.

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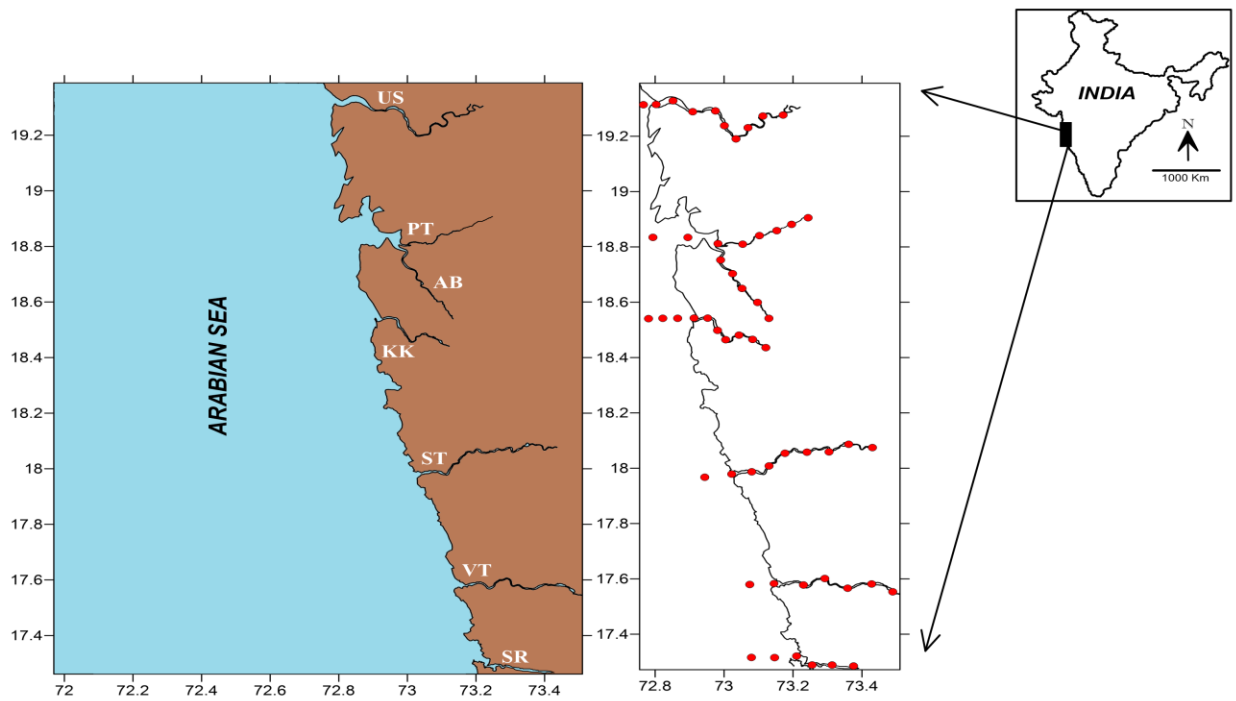


Fig. 1. Map of seven tropical estuaries of west coast of India along the eastern Arabian Sea showing the location of the sampling stations.

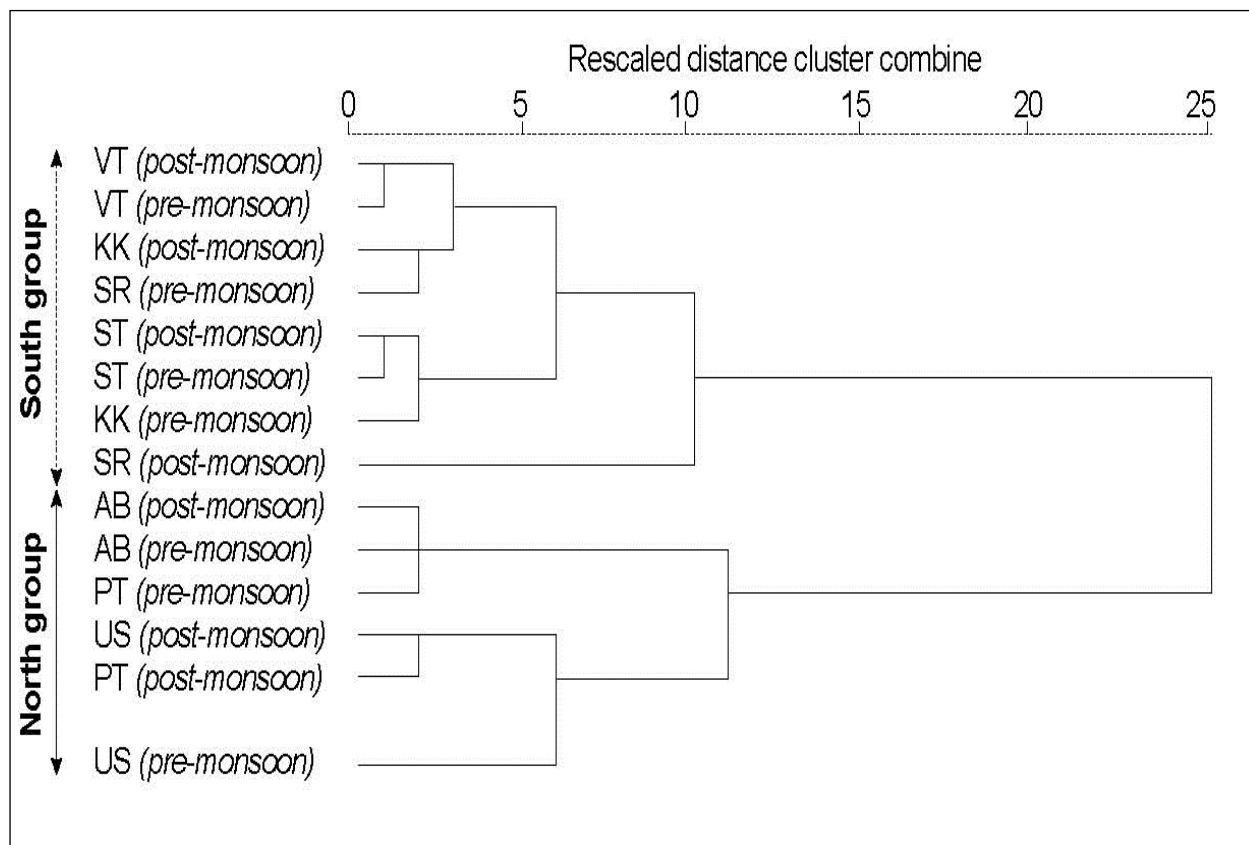


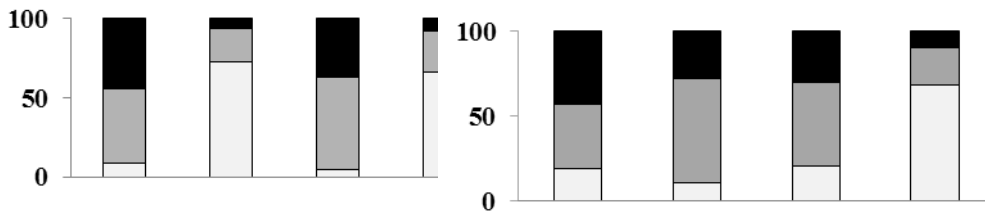
Fig. 2. Dendrogram resulted from hierarchical cluster analysis. Relationship of estuaries in a particular cluster represents their similar sedimentary organic biochemical parameters (C_{org} , N_{tot} , CHO, PRT and LPD) during post and pre-monsoon in the study area.

Post-monsoon

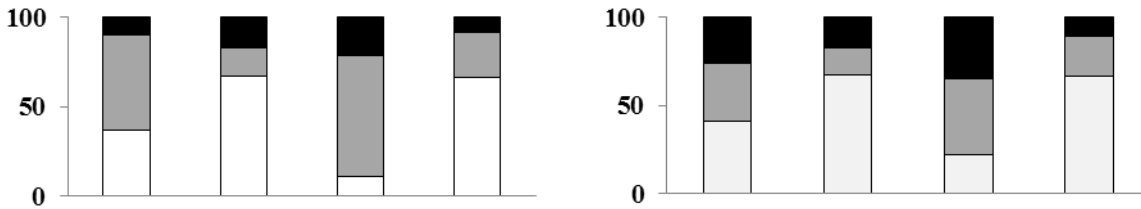
Pre-monsoon

US

■ Clay (%) ■ Silt (%) □ Sand (%)

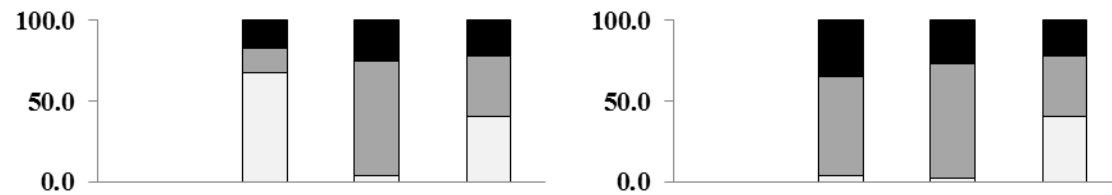


PT

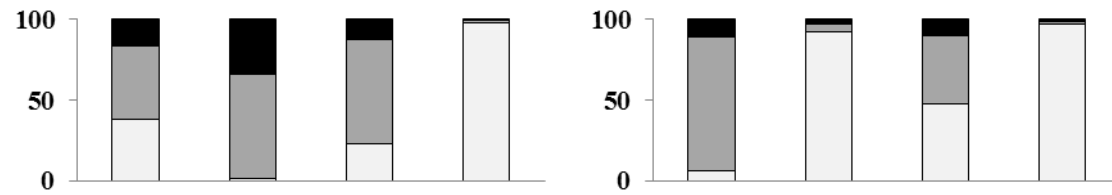


North group

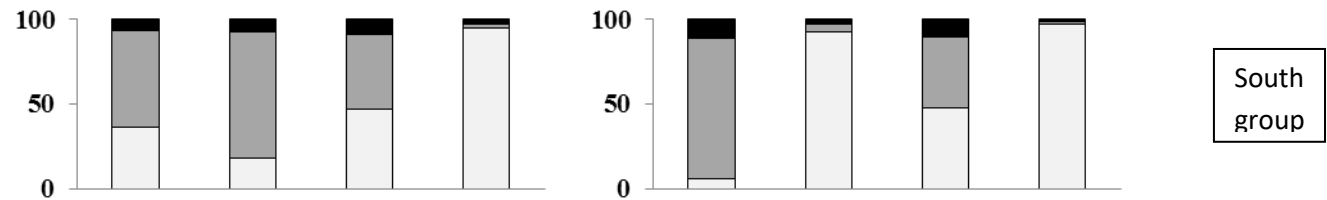
AB



KK

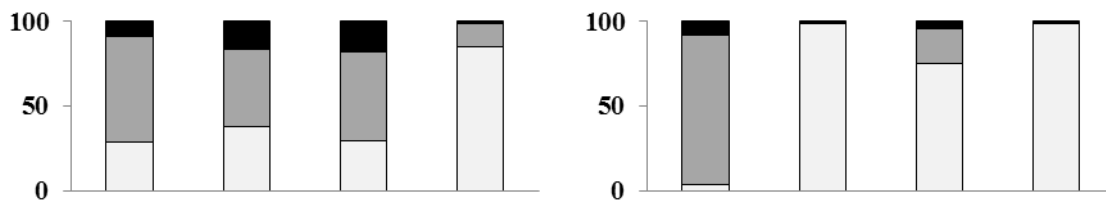


ST



South group

VT



SR

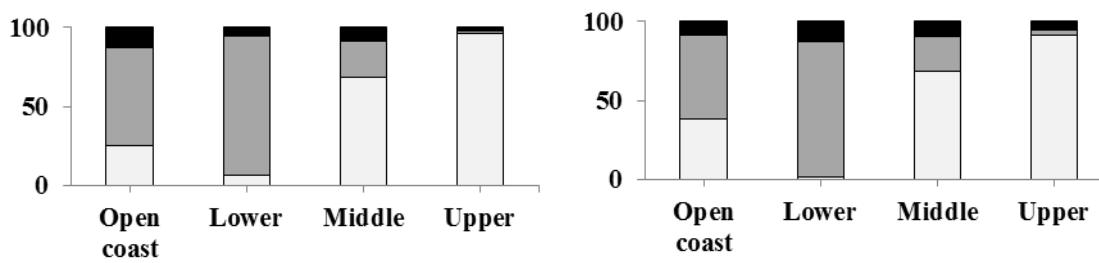


Fig. 3 Contribution of grain size (sand(<math><63 \mu\text{m}</math>), silt(>2 $\mu\text{m}</math>) and clay (<math><2 \mu\text{m}</math>)) in sediments during post-monsoon and pre-monsoon seasons along the seven studied estuaries. In the abscissa, represents upper, middle, lower and open coast zones.$

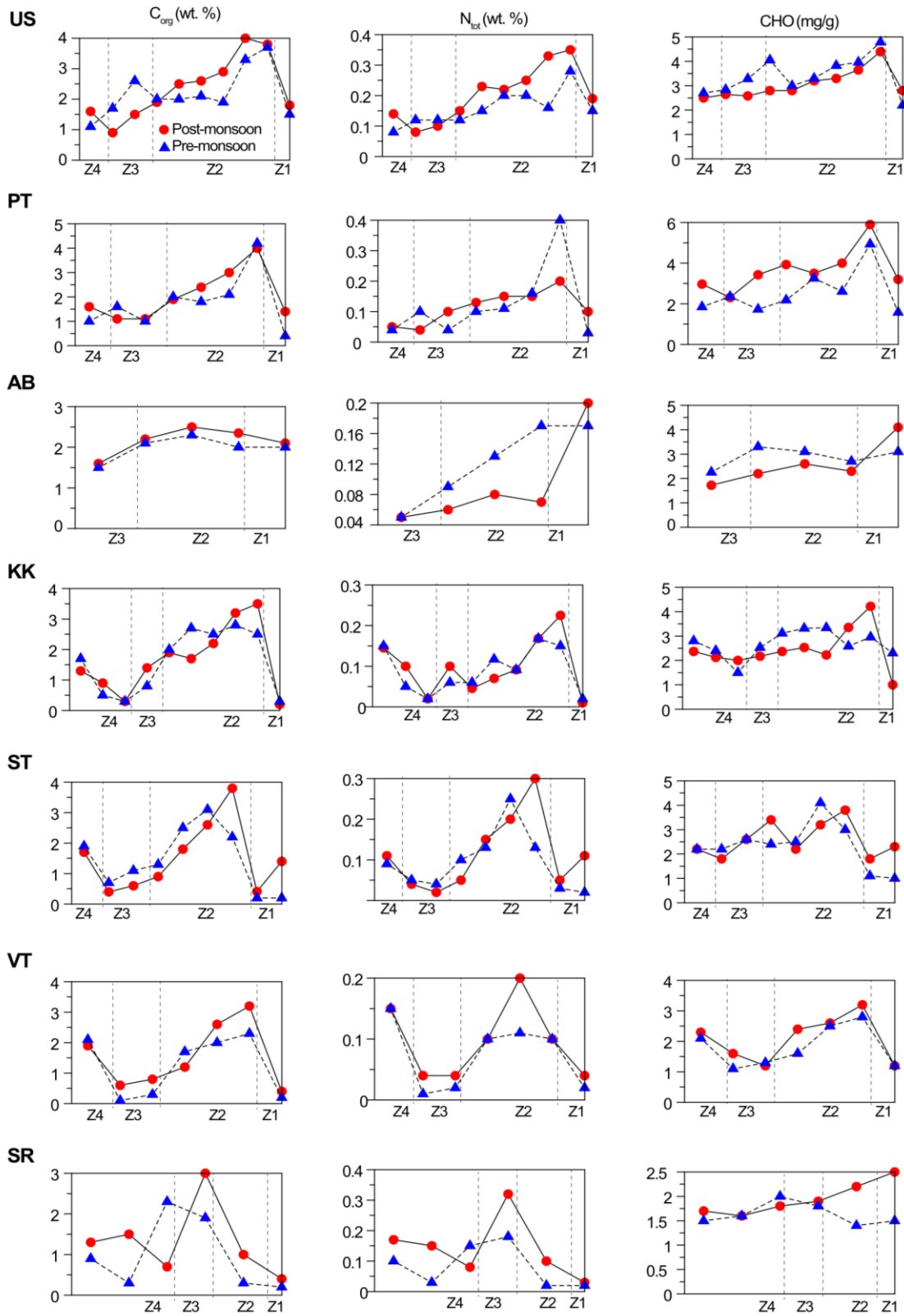


Fig. 4. Weight percentages of C_{org} , N_{tot} (%) and concentrations of CHO (mg/g) during pre-monsoon and post-monsoon seasons along the seven studied estuaries. In the abscissa, Z1, Z2, Z3 and Z4 represents upper, middle, lower and open coast zones of all the estuaries respectively.

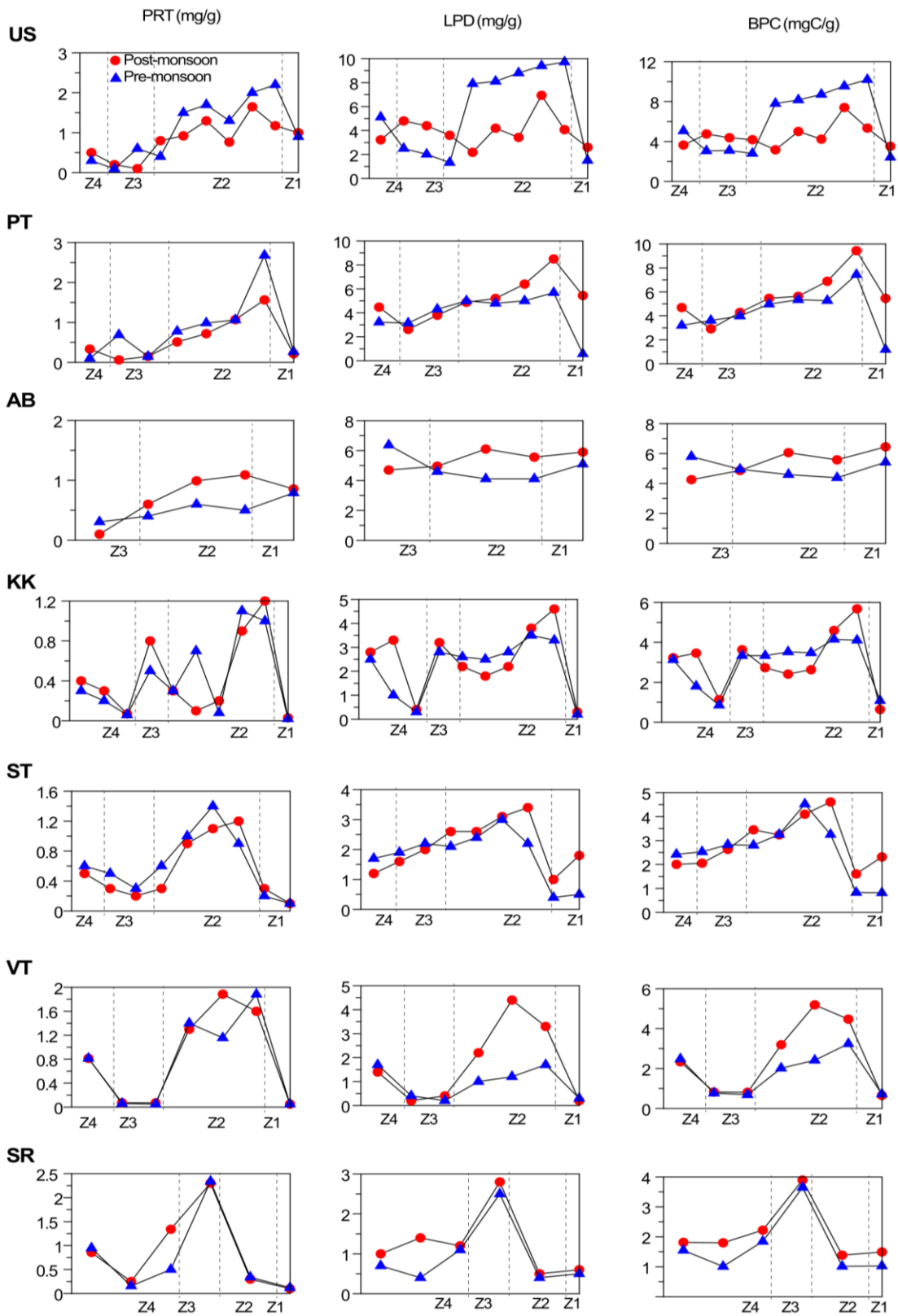


Fig. 5. Concentrations of PRT, LPD (mg/g) and BPC (mgC/g) during pre-monsoon and post-monsoon seasons along the seven studied estuaries. In the abscissa, Z1, Z2, Z3 and Z4 represents upper, middle, lower and open coast zones of all the estuaries respectively.

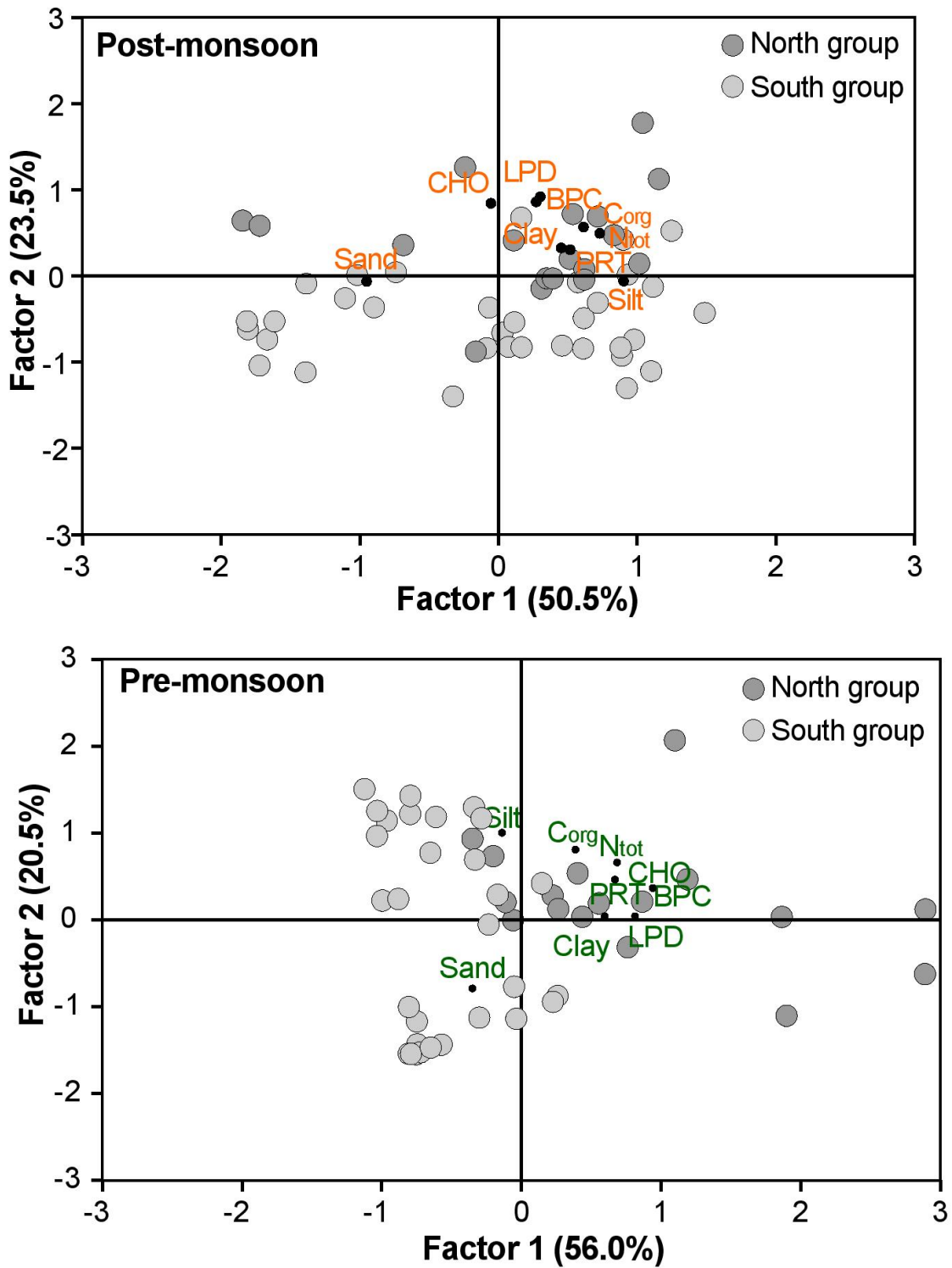


Fig. 6. Principal components analysis (PCA) representing loading pattern of various biogeochemical parameters in the sediments during post and pre monsoon in the study area.

Table 1. Panel A: General features of the studied river-estuary systems of Maharashtra.

Rivers/Estuary	Location	Depth (m)	Basin area (km ²)	L/H ratio	Rainfall (mm yr ⁻¹)	Annual flow (×10 ⁶ m ³)	Water yield (m ³ km ⁻² yr ⁻¹)	Effluent discharge Industry/Domestic
Ulhas (US)	19.307–19.307 °N	3.3–8.5	3804	0.20	3556	8793	2.31	0.17
	72.742–73.193 °E							
Patalganga (PT)	18.831–18.886 °N	3.1–6.0	940	0.05	3366	2056	2.19	1.00
	72.974–73.133 °E							
Amba (AB)	18.799–18.539 °N	3.0–5.5	740	0.14	3050	1467	1.98	1.88
	72.913–73.184 °E							
Kundalika (KK)	18.549–18.442 °N	4.5–10.0	825	0.06	3143	1685	2.04	1.00
	72.860–73.117 °E							
Savitri (ST)	17.973–18.090 °N	4.0–7.0	2889	0.05	3493	6558	2.27	0.80
	72.973–73.446 °E							
Vashishthi (VT)	17.581–17.551 °N	4.5–10.0	2238	0.08	3391	4933	2.20	0.58
	73.087–73.484 °E							
Shastri (SR)	17.315–17.279 °N	3.2–12.5	2174	0.08	3260	4607	2.12	–
	73.137–73.295 °E							

Panel B: Information on sample collection from river-estuary systems of Maharashtra, where Z1, Z2, Z3 and Z4 represents upper, middle, lower and open coast zones of all the estuaries respectively.

Estuary	Post-monsoon 2015				Pre-monsoon 2016			
	Zone 1	Zone 2	Zone 3	Zone 4	Zone 1	Zone 2	Zone 3	Zone 4
Ulhas (US)	1	6	2	1	1	6	2	1
Patalganga (PT)	1	4	2	1	1	4	2	1
Amba (AB)	1	3	1	-	1	3	1	-
Kundalika (KK)	1	5	1	3	1	5	1	3
Savitri (ST)	2	4	2	1	2	4	2	1
Vashishthi (VT)	1	3	2	1	1	3	2	1
Shastri (SR)	1	1	1	3	1	1	1	3

Table 2. Panel A: Correlation between sedimentary parameters in the NM (n =46). **Panel B:** Correlation between sedimentary parameters in the SM (n = 64) significance levels bolded $p < 0.05$.

Panel A												
	Sand	Silt	Clay	C _{org}	N _{tot}	C _{org} /N _{tot}	CHO	PRT	LPD	BPC	BPC/C _{org}	COM
Sand	1.00											
Silt	-0.74	1.00										
Clay	-0.50	-0.21	1.00									
C _{org}	-0.54	0.49	0.14	1.00								
TN	-0.32	0.29	0.09	0.88	1.00							
C/N	-0.14	0.22	-0.09	-0.29	-0.63	1.00						
CHO	0.06	0.01	-0.11	0.31	0.40	-0.37	1.00					
PRT	-0.32	0.23	0.16	0.77	0.82	-0.47	0.42	1.00				
LPD	-0.09	0.02	0.10	0.32	0.27	-0.11	0.22	0.40	1.00			
BPC	-0.18	0.14	0.08	0.73	0.81	-0.52	0.55	0.97	0.41	1.00		
BPC/C _{org}	0.44	-0.42	-0.10	-0.24	-0.16	0.03	0.22	0.09	0.21	0.16	1.00	
COM	-0.61	0.58	0.14	0.92	0.72	-0.08	0.09	0.47	0.20	0.40	-0.42	1.00
Panel B												
Sand	1.00											
Silt	-0.98	1.00										
Clay	-0.56	0.39	1.00									
C _{org}	-0.66	0.64	0.39	1.00								
TN	-0.63	0.64	0.27	0.84	1.00							
C/N	-0.02	0.01	0.07	0.12	-0.30	1.00						
CHO	-0.40	0.37	0.34	0.72	0.52	0.14	1.00					
PRT	-0.33	0.33	0.17	0.53	0.61	-0.20	0.31	1.00				
LPD	-0.44	0.40	0.39	0.70	0.57	-0.02	0.67	0.39	1.00			
BPC	-0.54	0.51	0.39	0.81	0.78	-0.07	0.75	0.68	0.75	1.00		
BPC/C _{org}	0.45	-0.41	-0.38	-0.50	-0.32	-0.30	-0.33	-0.01	-0.29	-0.18	1.00	
COM	-0.66	0.65	0.37	0.99	0.84	0.14	0.68	0.50	0.63	0.76	-0.52	1.00

Table 3. Mean with standard deviation (\pm) ratio of C_{org}/N_{tot} , BPC/C_{org} , PRT/CHO and LPD/CHO and during post-monsoon and pre-monsoon seasons along the seven studied estuaries. In the abscissa, Z1, Z2, Z3 and Z4 represents upper, middle, lower and open coast zones as per salinity gradient of all the estuaries respectively.

Area	Zone	C_{org}/N_{tot}		BPC/C_{org}		PRT/CHO		LPD/CHO	
		Post	Pre	Post	Pre	Post	Pre	Post	Pre
US	Z1	9.5 \pm 0.2	7.9 \pm 0.1	19.6 \pm 0.2	16.1 \pm 0.1	0.4 \pm 0.1	0.4 \pm 0.2	0.9 \pm 0.1	0.7 \pm 0.2
	Z2	11.5 \pm 0.6	9.3 \pm 1.2	15.8 \pm 2.9	36.0 \pm 7.7	0.3 \pm 0.1	0.5 \pm 0.1	1.2 \pm 0.4	2.4 \pm 0.2
	Z3	13.0 \pm 1.9	20.2 \pm 16.4	34.6 \pm 16.1	14.6 \pm 3.1	0.1 \pm 0.05	0.1 \pm 0.05	1.6 \pm 0.3	0.6 \pm 0.3
	Z4	11.4 \pm 0.1	7.9 \pm 0.2	22.8 \pm 0.2	46.0 \pm 0.2	0.2 \pm 0.1	0.1 \pm 0.05	1.3 \pm 0.2	1.9 \pm 0.1
PT	Z1	14.0 \pm 0.1	13.3 \pm 0.1	39.0 \pm 0.1	29.6 \pm 0.2	0.1 \pm 0.05	0.2 \pm 0.1	1.7 \pm 0.1	0.4 \pm 0.1
	Z2	18.7 \pm 2.3	13.3 \pm 2.9	23.3 \pm 0.3	24.2 \pm 6.0	0.2 \pm 0.1	0.4 \pm 0.2	1.5 \pm 0.1	1.5 \pm 0.4
	Z3	12.8 \pm 2.6	22.5 \pm 3.5	33.9 \pm 7.2	32.3 \pm 10.6	0.1 \pm 0.05	0.2 \pm 0.1	1.2 \pm 0.1	2.4 \pm 0.1
	Z4	29.8 \pm 0.2	20.5 \pm 0.1	27.9 \pm 0.2	27.3 \pm 0.1	0.1 \pm 0.05	0.2 \pm 0.1	1.3 \pm 0.1	1.5 \pm 0.1
AB	Z1	10.5 \pm 0.2	11.8 \pm 0.1	30.7 \pm 0.2	27.1 \pm 0.1	0.2 \pm 0.1	0.3 \pm 0.1	1.4 \pm 0.1	1.6 \pm 0.1
	Z2	33.8 \pm 2.2	17.6 \pm 4.7	23.4 \pm 0.9	21.8 \pm 1.5	0.4 \pm 0.1	0.2 \pm 0.05	2.3 \pm 0.2	1.4 \pm 0.1
	Z3	32.0 \pm 0.1	30.0 \pm 0.2	26.6 \pm 0.1	38.7 \pm 0.1	0.1 \pm 0.05	0.1 \pm 0.02	2.7 \pm 0.1	2.8 \pm 0.2
KK	Z1	20.0 \pm 0.2	15.0 \pm 0.1	31.9 \pm 0.1	36.0 \pm 0.1	0.03 \pm 0.01	0.01 \pm 0.01	0.3 \pm 0.2	0.1 \pm 0.05
	Z2	19.5 \pm 10.1	20.2 \pm 7.2	14.2 \pm 6.3	15.1 \pm 6.0	0.2 \pm 0.1	0.3 \pm 0.2	1.1 \pm 0.1	1.1 \pm 0.3
	Z3	14.0 \pm 0.1	13.3 \pm 0.1	25.9 \pm 0.2	41.7 \pm 0.2	0.4 \pm 0.05	0.2 \pm 0.1	1.5 \pm 0.05	1.1 \pm 0.1
	Z4	11.0 \pm 2.8	12.1 \pm 2.1	33.7 \pm 6.3	27.6 \pm 7.2	0.1 \pm 0.03	0.1 \pm 0.03	1.0 \pm 0.3	0.5 \pm 0.3
ST	Z1	10.5 \pm 3.2	10.0 \pm 2.4	27.8 \pm 16.0	41.3 \pm 0.4	0.1 \pm 0.05	0.1 \pm 0.05	0.7 \pm 0.2	0.4 \pm 0.1
	Z2	12.6 \pm 0.5	16.2 \pm 3.5	15.3 \pm 2.9	14.1 \pm 1.0	0.4 \pm 0.05	0.3 \pm 0.1	1.0 \pm 0.1	0.8 \pm 0.1
	Z3	19.3 \pm 10.1	18.2 \pm 8.1	44.5 \pm 6.6	27.8 \pm 7.5	0.1 \pm 0.05	0.2 \pm 0.1	0.8 \pm 0.1	0.9 \pm 0.01
	Z4	15.5 \pm 0.1	21.1 \pm 0.1	11.8 \pm 0.1	12.8 \pm 0.05	0.2 \pm 0.1	0.3 \pm 0.05	0.5 \pm 0.03	0.8 \pm 0.04
VT	Z1	10.0 \pm 0.1	10.0 \pm 0.2	16.3 \pm 0.1	36.4 \pm 0.1	0.04 \pm 0.1	0.04 \pm 0.01	0.2 \pm 0.04	0.3 \pm 0.1
	Z2	18.3 \pm 11.3	15.9 \pm 3.2	16.1 \pm 6.3	31.3 \pm 1.2	0.3 \pm 0.12	0.4 \pm 0.2	0.7 \pm 0.4	0.4 \pm 0.1
	Z3	17.5 \pm 3.5	12.5 \pm 3.5	11.9 \pm 2.5	49.9 \pm 37.9	0.1 \pm 0.01	0.05 \pm 0.01	0.2 \pm 0.1	0.3 \pm 0.1
	Z4	12.7 \pm 0.1	14.0 \pm 0.1	12.3 \pm 0.1	11.8 \pm 0.1	0.4 \pm 0.03	0.4 \pm 0.2	0.6 \pm 0.06	0.8 \pm 0.04
SR	Z1	13.3 \pm 0.1	10.0 \pm 0.1	19.5 \pm 0.1	20.3 \pm 0.1	0.04 \pm 0.1	0.1 \pm 0.05	0.2 \pm 0.05	0.3 \pm 0.1
	Z2	9.7 \pm 0.4	12.8 \pm 3.1	13.4 \pm 0.6	26.5 \pm 10.3	0.1 \pm 0.05	0.2 \pm 0.05	0.2 \pm 0.1	0.3 \pm 0.1
	Z3	8.8 \pm 0.1	15.3 \pm 0.1	31.8 \pm 0.2	8.0 \pm 0.2	1.2 \pm 0.3	1.3 \pm 0.2	1.5 \pm 0.1	1.4 \pm 0.2
	Z4	8.8 \pm 1.7	9.5 \pm 0.7	13.0 \pm 1.4	25.5 \pm 11.6	0.3 \pm 0.2	0.4 \pm 0.2	0.7 \pm 0.2	0.4 \pm 0.2

Table 4. Comparison of the present study with biochemical and elemental parameters from different estuaries in the world.

Study area	CHO (mg/g)	PRT (mg/g)	LPD (mg/g)	C/N	References
West coast of India	1.0–4.3	0.02–2.3	0.2–9.8	8.8–40.0	Present study
Cochin Estuary, India	0.4–1.3	0.11–0.53	0.12–5.8	0.39–35.1	Salas et al. (2015)
South eastern Arabian sea	0.4–3.5	0.1–7.3	0.9–5.1	–	Ramya et al. (2013)
East coast of India	2.8–4.7	–	–	15.0–23.0	Kumar et al. (2013)
Rio de la Plata Estuary, Uruguay	0.29–8.9	1.8–16.4	0.5–8.4	–	Venturini et al. (2012)
Yangtze Estuary, China	-	-	-	8.01–12.30	Liu et al. (2006)
Mundaka Estuary, Spain	0.2–5.7	0.0–1.7	0.3–5.0	–	Cotano and Villate (2006)
Lower St.Lawrence Estuary, Canada	7.58–10.7	0.11–0.4	0.82–1.47	–	Colombo et al. (1996)
River Estuary (Tyrrhenian Sea)	0.35–1.89	0.25–1.67	0.029–0.13	–	Fabiano and Danovaro (1994)

Table. 5. Benthic trophic classifications based on BPC (mgC/g) during post-monsoon and pre-monsoon seasons along the seven studied estuaries. In the abscissa, open coast lower, middle and upper zones of all the estuaries respectively. Where **E**= Eutrophic, **ME**= Mesotrophic and **OL**= Oligotrophic.

Area	Postmonsoon								Premonsoon							
	Open coast		Lower		Middle		Upper		Open coast		Lower		Middle		Upper	
	Trophi		Trophi		Trophi		Trophi		Trophi		Troph		Troph		Trophic	
	BPC	c	BPC	c	BPC	c	BPC	c	BPC	c	BPC	ic	BPC	ic	BPC	Status
	(mgC	Status	(mgC	Status	(mgC	Status	(mgC	Status	(mgC	Status	(mgC	Status	(mgC	Status	(mgC	
	/g)		/g)	s	/g)		/g)		/g)		/g)		/g)		/g)	
US	3.6	E	4.4	E	7.4	E	3.5	E	2.6	ME	3.2	E	10.5	E	2.4	ME
PT	2.1	ME	1.4	ME	6.7	E	5.5	E	2.9	ME	1.4	ME	7.0	E	1.2	ME
AB	-	-	1.4	ME	3.7	E	6.4	E	-	-	2.5	ME	4.0	E	5.4	E
KK	2.2	ME	5.0	E	4.0	E	0.6	OL	1.8	ME	3.6	E	4.5	E	1.1	ME
ST	2.0	ME	2.8	ME	4.0	E	2.0	ME	2.4	ME	2.8	ME	3.7	E	0.8	OL
VT	2.3	ME	0.8	OL	4.2	E	0.7	OL	2.5	ME	0.7	OL	2.6	ME	0.7	OL
SR	2.0	ME	4.0	E	2.9	ME	1.5	ME	1.5	ME	3.7	E	1.0	ME	1.0	ME