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Macrobenthic community of an anthropogenically influenced mangrove associated estuary on the East coast of India: An approach for ecological assessment

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The Mahanadi Estuarine System (MES), with a complex network of freshwater channels, rivers, and mangroves, is a leading seaport in State Odisha on the east coast of India, but subjected to intense human activity in recent years. Such anthropic impingements are known to impact sediment-dwelling biota adversely. However, information on the macrobenthic community of the MES is not well documented yet. Therefore, the primary objectives of this study (February 2013-March 2017) were to address knowledge gaps on the macrobenthic community structure vis-à-vis local environmental conditions and to evaluate the extent of anthropogenic disturbances on macrobenthos. The results from 264 benthic grab samples (van Veen, 0.04 m^2; 2 replicates × 12 GPS fixed locations × 3 seasons) revealed 73 taxa representing 64 genera and 48 families of macrobenthic fauna. The polychaetes (81.41%) and crustaceans (15.42%) were significant faunal groups that contributed mainly to the benthic population and diversity. Multivariate approaches using benthic community attributes and biotic indices (AMBI and M-AMBI) as proxy measures of environmental disturbances proved effective for appraisal. The correlations between the environmental parameters (temperature, pH, salinity) and community estimates were statistically significant. Hierarchical clustering analysis disclosed three major groups (Global R 0.70; $p < 0.002$) influenced by tolerant/opportunist species. The lower abundance, richness, diversity, and dominance of opportunistic species mark the signs of environmental stress.

The community health status remained unbalanced, as indicated by AMBI scoring. M-AMBI analysis contributed best in differentiating areas exposed to diverse impacts and indicated polluted community health status with moderate ecological quality. Our results reiterate the effective use of macrobenthos as bioindicators for ecological status and monitoring. The findings could be utilized for future monitoring assessments, translated into valuable information, and designed into well-defined sustainable management strategies for the MES.

KEYWORDS

macrobenthos, pollution monitoring, Mahanadi estuary, Odisha, Bay of Bengal, AMBI, M-AMBI

Highlights

- Comprehensive assessment of the macrobenthic fauna from a tropical mangrove-associated estuary in India.
- Differential benthic responses to anthropogenic interference examined through a suite of univariate and multivariate analyses.
- Less diverse benthic communities and more opportunistic species marked signs of local environmental stress.
- AMBI and M-AMBI indices differentiated benthic community health/ecological quality in relation to various anthropogenic impacts.
- Macrobenthos effective as bioindicators for habitat monitoring and assessment of the estuary.
- Recommendations for conservation and management of the Mahanadi estuary outlined.

Introduction

Estuaries are naturally stressed bionetworks that exhibit a high degree of variability in their environmental conditions (Elliott and Quintino, 2007). These highly productive ecosystems have been the focal points for various human activities, of which rapid industrialization and indiscriminate urbanization are accountable for divergent pressures and ecosystem degradation (Lotze et al., 2006; John et al., 2017; Dash et al., 2021). Together with extreme climatic events, unprecedented demands of a rapidly increasing population for space, development, and resources have resulted in changes across global estuaries and started questioning the future of the estuaries (Kennish, 2002; Wetz and Yoskowitz, 2013; Elliott et al., 2019). Given the limitations of physicochemical approaches for determining the effects of such disturbances, the importance of macrobenthic investigations are frequently emphasized (Dauvin et al., 2016; Belal, 2019).

With extended life spans, sedentary lifestyles, and varying thresholds of sensitivity to ambient water/sediment conditions, benthic organisms are excellent bioindicators of prolonged environmental variations, mirrored through fluctuations in species composition and abundance (Veiga et al., 2016; Sany et al., 2018a). Furthermore, the distribution patterns of macrobenthos are susceptible to a wide range of anthropogenic interferences and show spatial and temporal shifts accordingly (Dash et al., 2021). Therefore, studies on the macrobenthic communities are increasingly adopted for assessing the health of the aquatic ecosystems (Mulik et al., 2017; Borja et al., 2019; Mulik et al., 2020a; Mulik et al., 2020b; Pandey et al., 2021; Dauvin et al., 2021; Subramanian et al., 2021).

Many tropical estuaries, particularly in South and Southeast Asia, are polluted and over-exploited (Bae et al., 2017; Sarathy et al., 2022). In India, the estuaries have been reported with altered or degraded environmental quality owing to the inadvertent growth of industries and metropolises on the banks of the major rivers (Sigamani et al., 2015; Feebarani et al., 2016; Mulik et al., 2017; Mitra et al., 2018; Mulik et al., 2020a; Mulik et al., 2020b). The increased loads of municipal and industrial effluents, in amounts higher than the assimilatory capacity of the system, are accumulating pollutants and causing hypoxia-like conditions (Mitra et al., 2018; Mulik et al., 2020a; Kumar et al., 2021). Despite the large deltas with some luxuriant estuarine mangrove cover along the east coast of India (in contrast to the west coast), studies that have looked at the effects of changed environmental conditions on macrobenthic fauna are largely limited (Raut et al., 2005; Ansari et al., 2017; Bhowmik and Mandal, 2021; Dash et al., 2021; Pandey et al., 2021).

The Mahanadi estuary at Paradip in the State of Odisha (Figure 1), a leading maritime gateway on the east coast of India, is not exempt from the severe anthropogenic disturbances in recent times (Nayak, 2020). Port/harbor expansion, dredging, increased marine traffic, loss of mangroves, and aquaculture development, amongst others, are some regularly seen activities in the vicinity. Such events, not to mention the additional burdens of pollution and changes in physicochemical conditions of the estuary, show adverse impacts on the sediment-dwelling benthic communities (Nayak et al., 2018), making this study highly relevant.

Identifying the differential response of macrobenthos to environmental changes is crucial for their habitat protection. In this perspective, a suite of univariate and multivariate data analyses remains invaluable (e.g., Clarke et al., 2014; Sany et al., 2018b; Mulik et al., 2020a). Among others, the biotic indices such as AMBI (AZTI's Marine Biotic Index) and M-AMBI (Multivariate AMBI) are robust and used widely for coastal environmental monitoring and benthic quality assessment (Borja et al., 2000; Bald et al., 2005; Muxika et al., 2007; Borja et al., 2014). In addition, these indices glean complex ecological information into easily communicable and understandable scores for possible conservation/management insights (Pinto et al., 2009).

The present study was primarily aimed to provide a state-of-the-art appraisal of the macrobenthos at Mahanadi estuary. The objectives were - (i) to identify macrobenthic communities and their composition in relation to local environmental conditions as an approach for ecological assessment and (ii) to evaluate the extent of anthropogenic disturbances on macrobenthos through the application of marine biotic indices as proxy measures of environmental degradation. This is the first long-term investigation of the hitherto poorly explored Mahanadi Estuarine System (MES). Therefore, it can form the basis for future environmental monitoring, assessment, and management of the region.

Materials and methods

Study area

River Mahanadi, together with its three tributaries - Daya, Nuna, and Bhargavi, discharges into the Bay of Bengal in the State of Odisha on the east coast of India (20°17'08" N; 86°42'24" E) (Figure 1). The mixed semi-diurnal tides with a range of 1.45 to 2.20 m (mean, 1.29 m) reach 13 km upstream (depth 5.19 ± 1.11m) and support a rich diversity of the estuarine (mangrove) flora and fauna (Dey et al., 2013; Palei et al., 2014). According to the Indian Water Resources Information System (I-WRIS, 2021), Mahanadi is one of India's largest and longest (494 km) river systems, with a catchment area of over 65,628 km^2. The leading seaport, 'Paradip' - located 8 km south of the river mouth- is a hub for regional sea-borne trade. With a steadily rising population, the port township is fast developing as a core investment region for petroleum and chemicals (Hazra et al., 2020). Several industries like Indian Farmers and Fertilizers Cooperative Ltd., Paradip Phosphates Limited, Pellet Plant, Indian Oil Corporation Limited, Essar Steel, Ice manufacturing plants, Sea Food Processing units, besides many others, have sprung up in the immediate vicinity, with near denudation of once dense mangrove vegetation fringing the mudflats. Although fishing and cultivation are the traditional livelihood choices of the coastal residents, lucrative shrimp farming has gained precedence in recent years. As a result, the chemicals used for enhancing aquaculture production have been rampant. With the leaching of such substances into the waters, impacts on the estuary are imminent. Besides the untreated sewage from the township, effluents containing oil sludge, sulfur, ash, and gypsum released from industries are proven deterrent to the estuarine ecosystem (Hazra et al., opp. cit. and references therein; SPBO, 2020; Acharyya et al., 2021a; Acharyya et al., 2021b). Overall, the MES has become vulnerable to increased anthropogenic pressures and necessitates further assessment studies.

The climate of Mahanadi Delta is influenced by the premonsoon (March-May), postmonsoon (September-November), and winter (December-February) seasons every year. The southwest monsoon is the major monsoon season during which southwest directional winds blow from June to September. The northwest directional winds influence the winter months (December to February). The weather is typically marked by hot and humid conditions (31.46°C) in April-June and cool and dry (28.66°C) in December-January (https://www.worldweatheronline.com/). The southwest or summer monsoon (mid-June to September) brings heavy precipitation (average, 417.75 mm). The Mahanadi in spate discharges about 45,000 m^3 s^{-1} into the Bay of Bengal (Mohanti and Swain, 2005), reducing salinity and increasing fluvial loads in the nearshore waters. Furthermore, the southwest monsoon winds generate waves up to ~3 m high or more (Dash et al., 2020). As a result, the coast remains wave-dominated throughout the southwest monsoon and mixed wave and tide-dominated in the non-monsoon periods (Mohanti and Swain, opp. cit.).

Samples collection and laboratory analyses

Both biotic (macrobenthos) and abiotic (water and sediment) samples were collected trimonthly for nearly five years, covering the premonsoon, postmonsoon, and winter seasons (February 2013– March 2017). However, the pre-and postmonsoon sampling in 2016-2017 could not be completed due to logistic constraints.

A total of 12 sampling stations - from the river mouth to 13 km upstream (Figure 1), were fixed and reached with the help of a handheld GPS (Garmin Etrex 72H, Taiwan). The geographic location of the stations also represents various land-use land-cover types and habitat functioning in the vicinity. For instance, St. 1 (river mouth), St. 2 (adjacent to fishing harbor), and St. 11 (upstream area) act as migratory bird's foraging zone (BFZ). Similarly, Sts. 3-8 (adjoining mangroves) are the mangrove-associated zone (MAZ). Intensive shrimp farming (at Sts. 3, 6, and 7) and a factory named Indian Farmers Fertiliser Cooperative Limited (IFFCO) (at St. 8) are also present in the MAZ. The remaining Sts. 9, 10, and 12 adjacent to the country boat berthing facility and Essar Steel India Limited, a leading manufacturer and supplier of steel products and iron ore pellets, stand for the mangrove denuded zone (DZ). In addition, the two bifurcates of River Mahanadi at St. 12 bring considerable freshwater influx at the confluence (Figure 1).

Altogether, 264 sediment samples (in replicates) were collected with the help of a van Veen grab (0.04 m^2). After separating a small fraction of the sediment (~25g) for textural and organic matter analyses, each grab sample was transferred to a 500 µm sieve and gently washed with the seawater for macrobenthos. All specimens retained on the sieve were fixed in 5% buffered formaldehyde with 1% Rose Bengal for further processing and identification in the laboratory. Species-level identification of the macrobenthos (where possible) was carried out under a stereomicroscope (Leica, E24W, Germany) by following the standard literature (Fauvel, 1953; Fauchald, 1977; Abbott and Dance, 1982; Subba Rao et al., 1991; Blake et al., 2009; Yokoyama and Sukumaran, 2012; Muir and Hossain, 2014; Hutchings and Kupriyanova, 2018). The World Register of Marine Species (http://www.marinespecies.org/index.php) was followed to validate the scientific names. The faunal density at each station was expressed as ind. m^{-2}. Further, to estimate the wet biomass (gm^{-2}), preserved specimens were separated into different groups, kept on a mesh, and then moisture blotted out carefully with absorbent paper and weighed (OHAUS PAJ603 electronic balance).

Sand, silt, and clay (%) compositions in the sediment were determined by the pipette method (Krumbein and Pettijohn, 1938) and assigned the textural classes (Shepard, 1954). The organic matter (OM) (%) was estimated by the modified Walkey-Black wet-oxidation method (Gaudette et al., 1974). In the case of hydrographical parameters, salinity (psu), dissolved oxygen (DO) (mg l^{-1}), nitrite-nitrogen (NO$_2^-$) (µmol l^{-1}), and orthophosphate (PO$_4^-$) (µmol l^{-1}) were estimated by following the standard protocols (APHA, 1989; Grasshoff et al., 1999). Water temperature (using a mercury-filled thermometer of 0.5°C sensitivity), pH (using a Hanna HI 98107 with ±0.1 accuracy), depth (m) (using echo sounder), and transparency (m) (using a Secchi disc) were measured *in situ*. The instruments were calibrated before recording *in situ* variables in the field.

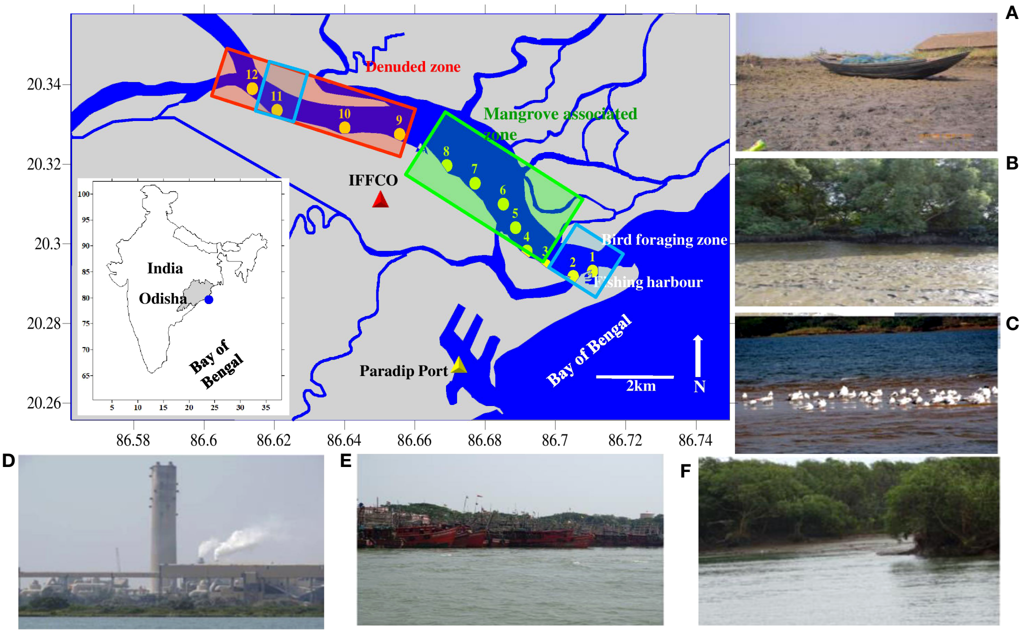

FIGURE 1
Mahanadi estuary in State Odisha on the east coast of India. The sampling stations (1-12) cover the ecotone influenced by the tides, i.e., from the river mouth to 13 km upstream. Examples of each habitat and sources of disturbances are denoted. **(A)** Denuded zone; **(B, C)** Mud flat and bird foraging zone, **(D)** IFFCO factory; **(E)** Fishing harbour, and **(F)** Mangrove associated zone.

Data treatment and statistical analyses

The faunal diversity indices such as mean abundance, species richness (*S*), and Shannon-Wiener index (*H'*) were computed using the PRIMER *v*.7 software (Plymouth Routines in Multivariate Ecological Research) (Clarke and Gorley, 2015). The (square root-transformed) data were used for Bray-Curtis similarity (clustering through hierarchical group-average linking) and non-metric multidimensional scaling (nMDS) ordinations. The significance of sample groupings was tested through the Analysis of Similarities (ANOSIM), whereas confirmatory evidence of the faunal assemblages was provided through the Similarity Profile Analysis (SIMPROF) (Clarke and Ainsworth, 1993). The species abundance matrix was represented by a shade plot where the gradation of shade from grey to black is linearly proportional to the increase in species abundance (Clarke and Gorley, 2015). The unconstrained binary divisive clustering (UNCTREE) analysis further examined both sample and species associations. The environmental data were normalized and subjected to Principal Component Analysis (PCA) to distinguish the sampling sites in relation to their (local) environmental conditions. The analysis of variance (ANOVA) tests was used to probe the spatial and temporal differences. The PCA was carried out using PRIMER *v*.7.

Biotic indices for environmental assessment

AMBI and M-AMBI indices were used to assess the gradient of anthropogenic stress across the MES. The index scores were derived from the AMBI *v*.6 software (http://www.ambi.azti.es). AMBI index is a univariate measure that uses a 'differential weighting' algorithm based on the classification of benthic species into five Ecological Groups (EGs) (i.e., EGI - species very sensitive; EGII - indifferent to enrichment; EGIII - tolerant to excess OME (organic matter enrichment); EGIV - second-order opportunistic species and, EGV -first-order opportunistic species) (Grall and Glémarec, 1997). The macrobenthos of Mahanadi estuary were assigned to different EGs by following the AMBI *v*.6 December 2020 taxa list. In addition, a few taxa not identified up to species level or not found in the AMBI database were also assigned for their respective EGs availing the WORMS database. However, 18.7% of total taxa were either not assigned to any EG or ignored due to irrelevant species (cf. Borja and Muxika, 2005).

The scores of the AMBI index were used to categorize the ecological quality of the estuary into five classes based on a scale from 0 to 7 (0-1.2: high, 1.2-3.3: good, 3.3-4.3: moderate, 4.3-5.5: poor and, >5.5: bad). On the other hand, M-AMBI is a multimetric index that derives scores from multiple factors (species richness, Shannon-Weiner diversity index, and AMBI scores). Further, it requires setting a reference condition (Muxika et al., 2007) of a high ecological quality ratio (EQR) of environmental and biological parameters specific to the habitat (Borja et al., 2012). Reference conditions are characterized by high biological and environmental quality elements giving the site a high ecological quality ratio (EQR) compared to the impacted site (Bigot et al., 2008). The Water Framework Directive (WFD) offers four criteria to select reference conditions: (1) pristine or minor disturbance, (2) historical data, (3) predictive modelling, and (4) expert judgment (Basset et al., 2013). Since finding the less disturbed or pristine environment is as difficult as getting the historical data in the era of 'Anthropocene,' it is always prudent to perform predictive modelling for setting the reference condition. Therefore, an internal control with high diversity, richness, and low AMBI from the dataset was used to set the reference target, and the M-AMBI scores were calculated as suggested by Muxika et al. (2007). The scores of M-AMBI were used to qualify the samples into five grades based on a scale from 0 to 1 (>0.77: high, 0.77–0.53: good, 0.53–0.38: moderate, 0.38–0.20: poor, and <0.20: bad). Procedures adopted to estimate indices scores, algorithm, boundary limits, and community health/ ecological quality classifications were based on the WFD scale of indices detailed by Equbal et al. (2017).

The pairwise Mann–Whitney U test was applied to assess differences on a seasonal scale within the faunal groups. Differences were considered significant at $p<0.05$ for all power test analyses. Finally, Pearsons' correlation coefficient test was carried out to find the possible influence of environmental parameters on biotic indices (Graph Pad Software, USA).

Results

Physico-chemical characteristics of water

The water temperature ranged from 21.5 to 36.0°C (mean, 28.34 ± 1.08°C), with the lowest measurements during winter and the highest during premonsoon (Table 1). The upper reaches were relatively warmer than the lower reaches of the estuary (Figure 2). The water pH was slightly alkaline - especially downstream (>7.5), and varied significantly between the seasons (two-way ANOVA $F = 19.89$, $p < 0.01$). With increasing salinity from upstream to downstream, brackish water conditions (9.26 ± 1.87 psu) prevailed along the estuary's entire (13 km long) stretch. Seasonal salinity changed in the order of winter > premonsoon > postmonsoon. The sampling stations in the proximity of industries (e.g., Sts. 8, 9, 10) showed less DO than those adjoining mangroves (Sts. 5, 6, 7). There was a

TABLE 1 Hydrographical and sediment characteristics of Mahanadi estuary during February 2013-March 2017.

Environmental parameters	Premonsoon (n = 36)	Postmonsoon (n = 36)	Winter (n = 60)	Mean (n = 132)
Water				
Temperature (°C)	26.00-37.00	24.00-35.00	21.00-31.00	21.50-36.00
	(31.38 ± 1.49)	(30.03 ± 1.22)	(25.51 ± 1.19)	(28.34 ± 1.08)
pH	1.33-7.96	3.75-8.32	5.93-9.23	2.27-9.19
	(6.86 ± 0.45)	(7.34 ± 0.39)	(7.86 ± 0.26)	(7.44 ± 0.24)
Salinity (psu)	2.49-22.41	0.13-7.04	3.07-24.98	0.13-23.38
	(10.69 ± 1.55)	(0.98 ± 0.48)	(13.37 ± 1.78)	(9.26 ± 1.87)
Dissolved oxygen (mg l^{-1})	0.16-7.52	2.40-8.00	0.80-8.96	1.04-8.56
	(4.31 ± 0.73)	(5.26 ± 0.69)	(4.44 ± 0.81)	(4.63 ± 0.44)
Nitrite-nitrogen (µmol l^{-1})	0.84-34.83	0.29-6.98	0.32-25.24	0.34-21.23
	(4.21 ± 1.51)	(1.90 ± 0.38)	(3.31 ± 1.21)	(3.17 ± 0.75)
Orthophosphate (µmol l^{-1})	0.08-29.16	0.08-20.60	0.37-23.74	0.31-22.62
	(5.55 ± 2.18)	(4.34 ± 1.55)	(3.79 ± 1.19)	(4.42 ± 1.06)
Transparency (m)	0.34-0.85	0.21-0.55	0.64-1.77	0.21-1.77
	(0.55 ± 0.05)	(0.35 ± 0.03)	(0.95 ± 0.09)	(0.62 ± 0.18)
Depth (m)	2.00-7.00	5.00-12.00	3.00-9.00	2.00-12.00
	(4.00 ± 0.60)	(7.00 ± 0.70)	(5.00 ± 0.53)	(5.19 ± 1.11)
Sediment				
Sand (%)	14.11-98.85	3.27-94.14	5.94-95.64	3.27-98.85
	(45.80 ± 9.83)	(41.99 ± 13.60)	(53.00 ± 8.46)	(48.03 ± 6.52)
Silt (%)	1.10-85.79	5.84-96.28	4.31-93.99	1.10-96.28
	(53.94 ± 9.86)	(57.86 ± 13.57)	(46.90 ± 8.45)	(51.81 ± 6.51)
Clay (%)	0.04-0.76	0.02-0.76	0.00-0.76	0.00-0.76
	(0.26 ± 0.11)	(0.15 ± 0.09)	(0.10 ± 0.04)	(0.16 ± 0.05)
Organic matter (%)	0.24-6.63	0.28-4.05	0.07-5.08	0.07-6.63
	(1.70 ± 0.37)	(1.96 ± 0.44)	(1.67 ± 0.28)	(1.76 ± 0.24)

Values are given as minimum-maximum (mean ± standard error).

significant difference in DO between pre-and postmonsoon periods (one-way ANOVA *F* =4.61, $p< 0.05$).

The distribution of dissolved nutrients revealed higher concentrations of NO_2^- (3.17 ± 0.75 µmol l^{-1}) and PO_4^- (4.22 ± 1.06 µmol l^{-1}) at the stations close to shrimp farms and industries (e.g., Sts. 7, 8, 11). Nutrient enrichment was high during the premonsoon, followed by postmonsoon and winter seasons (Table 1). The sampling stations subjected to higher anthropogenic intervention and upstream fluvial loads (Sts. 7-12) also had a lower water column transparency. The waters are more turbid for postmonsoon (0.35 ± 0.03) than premonsoon (0.55 ± 0.05) or winter (0.95 ± 0.09). Station-wise environmental parameters for each year and season are provided as Supplementary Data (STable 1).

Sediment characteristics

The estuarine sediments were comprised mostly of sand (48.03 ± 6.52) and silt (51.81 ± 6.51) (Table 1), with three distinct textural classes (i.e., silty sand, sandy silt, and silt). The OM ranged from 0.07 to 6.63% and was rather high at the creek/canal confluence locations (Figure 2). The correlation between textural grades and OM was clear. For instance, sediments from the river mouth (St. 1) and upstream (St. 12) with a high sand composition contained less OM in contrast to the mangrove sediments (Sts. 2-9) with a high silt composition. Seasonally, silt was distinctive of the postmonsoon. The sediment textural classes also indicated significant spatial and temporal variations (two-way ANOVA, sand *F*=3.23, $p < 0.05$; silt *F*=3.18, $p < 0.05$; clay *F*=10.89, $p < 0.01$).

The PCA revealed significant eigenvalues (>1), and the percentage of variance was 31.9% for PC1, followed by 26.9% for PC2. While most stations in the MAZ with silt and OM were on the positive side of the two axes, the sites of the DZ with a sand abundance were on the negative side (Figure 3). Overall, the first axis had segregation of stations based on their sediment nature, and the second axis was based on their water characteristics. The stations belonging to BFZ were closely associated with the water quality (salinity, DO, pH, NO_2^-) (Figure 3).

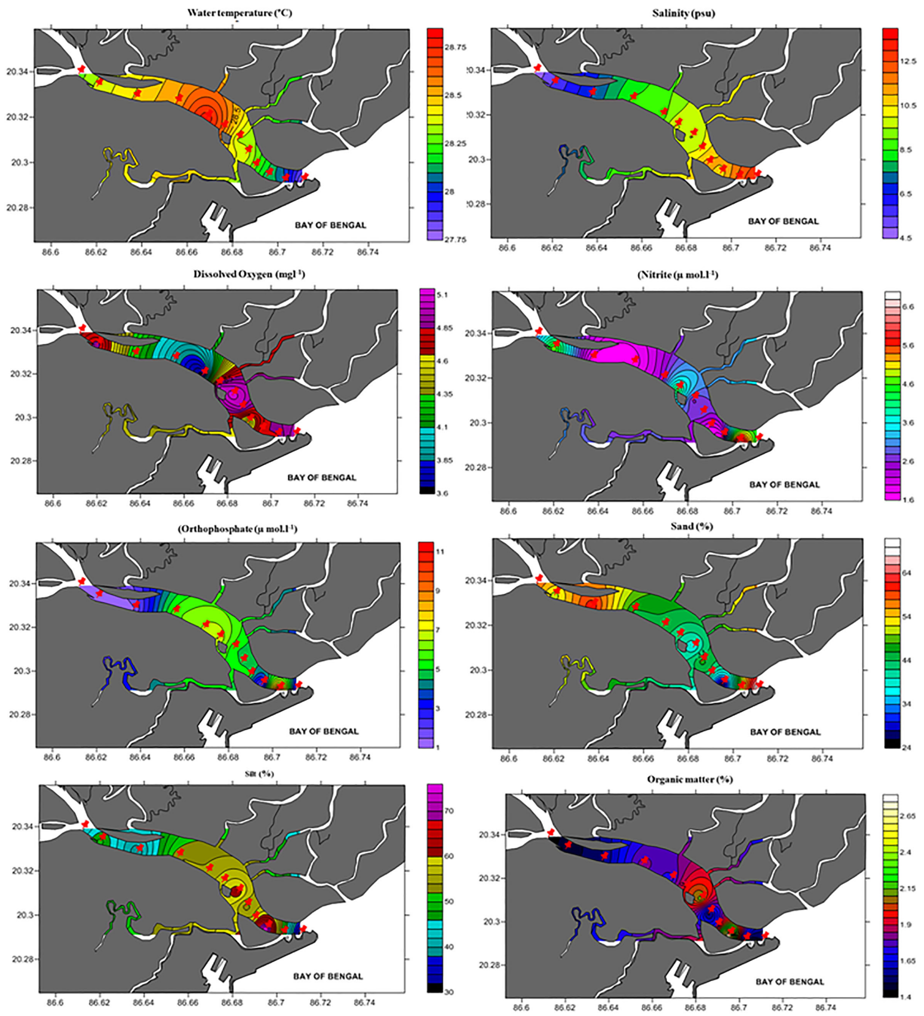

FIGURE 2
Spatial distribution patterns of hydrographical (water temperature, salinity, dissolved oxygen, nitrite, and orthophosphate) and sediment (sand, silt, and organic matter) variables in Mahanadi estuary.

Macrobenthic community

The present study recorded 100,500 individuals from 73 taxa, 64 genera, and 48 families represented by major faunal groups such as Polychaeta, Brachiopoda, Sipuncula, Crustacea, Mollusca, Echinodermata, and Pisces. However, polychaetes (81.41%), and crustaceans (15.42%) were found to be important in terms of their abundance (Table 2). Within Polychaeta, families such as Spionidae (9 species), Capitellidae (4 species), and Nereididae (4 species) were the most diverse and dominant groups, contributing 48% to the total population. The notable species of polychaetes were nereid *Perinereis cavifrons*, nephtyid *Micronephthys oligobranchia*, spionids *Dipolydora coeca*, *Malacoceros indicus*, and *Polydora cornuta*. The important species of crustacean and molluscs included *Victoriopisa chilkensis*, *Psammacoma gubernaculum*, and *Nassarius stolatus*, with their juvenile populations (Table 2).

The macrobenthic faunal abundance ranged between 50 and 3,213 ind. m^{-2} (760 ± 727) (Table 2) was high at the BFZ in winter (mean, 2,288 ind. m^{-2}) and postmonsoon (3,213 ind. m^{-2}). In particular, the prevalence of *P. cavifrons* for these two seasons (773-970 ind. m^{-2}) is noteworthy. The faunal abundance of the BFZ varied significantly between premonsoon and postmonsoon (Mann–Whitney test, $p = 0.00$), whereas it differed between premonsoon and winter for the MAZ (Mann–Whitney, $p = 0.03$). The wet weight biomass was low in upstream (e.g., 0.03 gm^{-2} at St. 9) than in the downstream areas (25 gm^{-2} at St. 2). The macrobenthic faunal abundance data (Polychaeta, Mollusca, and Crustacea) tested for seasonal, species and station wise changes together with their interaction effects revealed significant

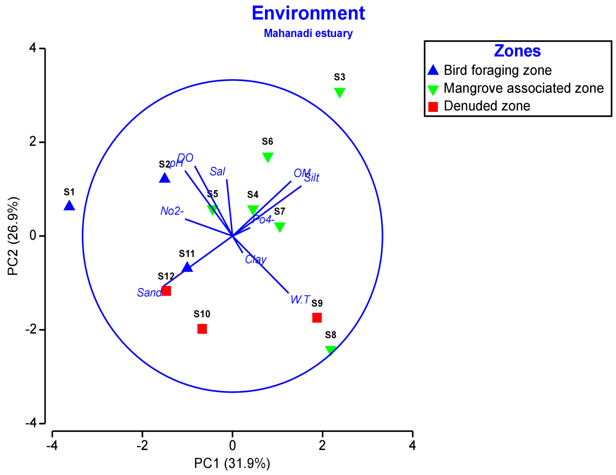

FIGURE 3
Principal Component Analysis (PCA) depicting the influence of environmental variables on the sampling (1-12) sites of the Mahanadi estuary during 2013-2017.The circle represents the correlation circle, and the orientation of the environmental parameters (lines) approximate their correlation to each other and to the ordination axes (DO = dissolved oxygen, Sal = salinity, OM = total organic matter, NO_2^- = nitrite-nitrogen, $PO4^-$ = orthophosphate, WT = water temperature). The MAZ (n = 66) – Mangrove associated zone includes St. 3, 4, 5, 6, 7, and 8, The BFZ (n = 33) – Birds foraging zone includes St. 1, 2 and 11, and the DZ (n = 33) – Denuded zone is represented by St. 9, 10 and 12.

differences, particularly for the molluscs (Table 3). Station-wise data on macrobenthic faunal abundance for each season were provided in the supplementary information (STable 2).

Macrobenthic assemblages

The abundance and distribution of 49 macrobenthic species at one or more sampling stations in the estuary accounted for ≥1% of the total population. Hierarchical clustering and nMDS plots have shown a clear-cut separation of the sampling stations into three major faunal groups (Global R 0.70; $p < 0.002$) (Figure 4). Group I, representing the BFZ (Sts. 1, 2, and 11), was dominated by *Perinereis cavifrons*, *Cossura coasta*, and *Dendronereis aestuariana* species ($\pi = 1.07$, $p < 0.07$), whereas Group II, for the MAZ (Sts. 3-8), is characterized by *Micronephtys-Victoriopisa-Heteromastus* assemblage. The sampling sites of DZ (Sts. 9, 10, and 12) as Group III contained *Cossura-Dipolydora-Malacoceros* assemblage. The UNCTREE analysis further confirmed the presence of these three faunal clusters (BFZ - Global *R*: 1, B%: 31.1, π: 2.59; MAZ- Global *R*: 0.61, B%: 48, π:1.06; DZ - Global *R*: 1, B%: 64.2, π: 1.07 (Figure 5).

Ecological groups (EGs)

Altogether, 61 macrobenthic species (out of 73) were categorized into their corresponding EGs (Table 2). Except for EGV (one species), the other groups were diverse and represented by 12-17 taxa. The highest faunal (mean) density was contributed by EGIV (36.4%), followed by EGII (20.8%), EGIII (20.5%), EGI (19.5%), and EGV (2.7%). The species such as *Heteromastus filiformis*, *C. coasta*, *D. coeca* (of EGIV), *P. cavifrons* (EGIII), *M. oligobranchia* (EGII), and *V. chilkensis* (EGI) were abundant, and collectively formed 60% of the total population. The faunal composition of MAZ (41.5%) and DZ (38.3%) was dominated by EGIV organisms, while BFZ (36.6%) by the EGIII (Figure 6). Seasonally, both premonsoon (41.7%) and winter (35.3.%) periods were characterized by EGIV and the postmonsoon (35.3.%) by EGIII species.

AMBI and M-AMBI indices

According to the AMBI scores, the estuary's ecological quality was *good* throughout except for St. 8, which had *moderate* conditions (Table 4). The AMBI scores improved from the premonsoon to the winter period. In this context, the samples with *poor* to *moderate* status from MAZ and BFZ (Sts. 2 and 7-9) in the premonsoon were represented by *moderate* to *good* status during the postmonsoon and winter (Figure 6B). The differences between premonsoon and winter were significant (Mann-Whitney, p = 0.01). Also, the sampling stations in the DZ were depicted with *good* ecological quality. However, in terms of community health, the estuary was unbalanced and polluted (Table 4).

In contrast to AMBI, the M-AMBI scores classified around 60% of the samples as *moderate* and 33.3% as *good* quality. M-AMBI followed a trend similar to that of AMBI, improving sample grades from the premonsoon to the winter period (Figure 6C). Except for St. 12 and St. 9 (DZ), where samples

TABLE 2 Numerical abundance of macrobenthic fauna and their assignment to ecological groups (EGs-Ecological groups, NA-Not assigned, IG-Ignored, SD-standard deviation).

Species/Taxa	EGs	Mean (ind.m^{-2})	SD	Min	Max	% Contribution	% Relative frequency
Polychaeta							
Orbinia sp.	IV	0.9	3.5	13	25	0.11	6.06
Aricidea sp.	NA	11.9	28.7	13	150	1.57	31.06
Cossura coasta	IV	48.6	194.3	13	1388	6.38	17.42
Cossura sp.	IV	24.5	80.6	13	550	3.22	24.24
Boccardia sp.	III	0.2	2.2	13	25	0.02	0.76
Heterospio sp.	II	1.1	8.5	13	75	0.15	2.27
Malacoceros indicus	III	23.6	73.1	13	713	3.10	38.64
Dispio sp.	III	0.5	2.4	13	13	0.06	3.79
Magelona cincta	I	7.7	23.3	13	138	1.01	12.12
Polydora cornuta	IV	22.8	210	13	2388	3.00	6.82
Dipolydora coeca	IV	47.3	127.8	13	900	6.22	38.64
Pseudopolydora kempi	IV	2.9	10.2	13	75	0.39	10.61
Paraprionospio sp.	IV	5.7	32.7	13	363	0.75	11.36
Prionospio polybranchiata	III	8	33.6	13	250	1.04	12.88
Cirriformia filigera	IV	0.8	5.9	13	63	0.10	2.27
Capitella species complex	V	10.1	35.2	13	288	1.33	15.91
Heteromastus filiformis	IV	61	112.6	13	588	8.01	48.48
Mediomastus sp.	III	7.2	39.9	13	388	0.94	6.82
Notomastus aberans	III	2.8	12.8	13	88	0.37	6.06
Euclymene annandalei	I	6.1	31.5	13	288	0.80	9.09
Hypereteone barantollae	II	0.7	2.8	13	13	0.09	5.30
Pisione sp.	I	0.3	1.9	13	13	0.04	2.27
Hesione sp.	II	0.3	2.4	13	25	0.04	1.52
Ancistrosyllis sp.	III	0.3	3.3	38	38	0.04	0.76
Hermundura annandalei	II	9	28.3	13	188	1.18	18.18
Syllis sp.	II	0.8	3.4	13	25	0.10	5.30
Perinereis cavifrons	III	126.9	467.3	13	2788	16.66	19.70
Namalycastis indica	IV	0.3	2.4	13	25	0.04	1.52
Dendronereis aestuarina	III	22.4	83.2	13	800	2.95	28.03
Neanthes chingrighattensis	IV	21.8	54.1	13	300	2.86	36.36
Glycera alba	IV	10.6	22.2	13	125	1.39	29.55
Glycera sphyrabrancha	II	16.4	45.4	13	300	2.15	20.45
Micronephthys oligobranchia	II	80	138.7	13	1000	10.51	56.06
Nephtys polybranchia	II	0.9	8.8	13	100	0.12	2.27
Cryptonome parvecarunculata	IG	1	8	13	88	0.14	3.03
Diopatra sp.	I	4.1	14.2	13	88	0.53	9.85
Lumbrineris simplicis	II	2.3	6.3	13	38	0.30	13.64
Lumbrinereis sp.	II	0.6	3.4	13	25	0.07	3.03
Sternaspis sp.1	III	8.4	42.3	13	375	1.11	9.85
Sternaspis sp. 2	III	3	15.1	13	100	0.40	5.30
Melinna aberrans	III	5.3	18.9	13	150	0.70	12.12
Pectinaria sp.	I	0.4	2.6	13	25	0.05	2.27
Terebella ehrenbergi	III	0.9	3.8	13	25	0.11	5.30
Myriochele sp.	II	4.8	18.3	13	150	0.63	12.12
Fabriciola sp.	I	4.8	15.1	13	88	0.63	15.15
Brachiopoda							
Lingula sp.	I	2.3	10	13	88	0.30	7.58

(Continued)

TABLE 2 Continued

Species/Taxa	EGs	Mean (ind.m^{-2})	SD	Min	Max	% Contribution	% Relative frequency
Sipunculida							
Sipunculid sp.	I	0.9	6.9	13	75	0.11	2.27
Crustacea							
Belzebub hanseni	NA	0.2	1.5	13	13	0.02	1.52
Paracaprella pusilla	I	2.6	7.4	13	38	0.34	12.88
Corophium volutator	III	12.6	129.6	25	1488	1.65	3.79
Victoriopisa chilkensis	I	76.6	172	13	1525	10.06	69.70
Cumacid sp.	I	6.3	39.1	13	413	0.82	9.09
Cyathura sp.	III	5.3	34.1	13	275	0.70	6.82
Exosphaeroma parva	III	3.3	23.2	13	250	0.44	4.55
Sphaeroma sp.	II	3	18.3	13	150	0.40	5.30
Harpacticid sp.	IG	0.5	5.4	63	63	0.06	0.76
Macrobrachium sp.	NA	5.7	16.5	13	88	0.75	15.91
Clibanarius sp.	IG	0.5	2.4	13	13	0.06	3.79
Crab juveniles	IG	0.9	4.3	13	38	0.12	6.06
Gastropoda							
Paratectonatica tigrina	II	0.7	7.6	88	88	0.09	0.76
Pirenella cingulata	I	0.4	2.6	13	25	0.05	2.27
Nassarius foveolatus	II	0.2	2.2	25	25	0.02	0.76
Nassarius stolatus	II	2.3	8	13	63	0.30	9.85
Agaronia gibbosa	IG	0.2	1.5	13	13	0.02	1.52
Gastropod juveniles	NA	2.5	6.4	13	38	0.32	15.91
Bivalvia							
Nucula sp.	I	0.2	2.2	25	25	0.02	0.76
Acrosterigma variegatum	III	0.1	1.1	13	13	0.01	0.76
Psammacoma gubernaculum	I	3.9	18.8	13	175	0.51	10.61
Meretrix sp.	I	0.3	1.9	13	13	0.04	2.27
Bivalve juveniles	IG	2.5	6.8	13	38	0.32	13.64
Echinoderms							
Ophiuroid juveniles	II	1.4	5	13	38	0.19	9.09
Pisces							
Periophthalmus sp.	IG	3.9	10.9	13	88	0.51	18.18
Boleophthalmus boddarti	IG	1.3	10.2	13	113	0.17	3.79
Diversity indices							
Abundance (ind. m^{-2})		760.6	727.9	50	3213		
Biomass (g m^{-2})		1.8	3.4	0.03	25		
Species richness (*S*)		8.7	4.6	2	24		
Shannon-Weiner index ($H'log_2$)		2.2	0.8	0.1	3.9		

The sample size n = 132 (mean of duplicate 264 grab samples).

were downgraded from *good* (premonsoon) to *moderate* (postmonsoon and winter) and *moderate* (premonsoon and postmonsoon) to *poor* condition (winter). A unidirectional shift in quality grades was observed at St. 2 (BFZ), where samples upgraded from *poor* (premonsoon) to *moderate* (postmonsoon) and *good* condition (winter). In contrast, the samples from Sts. 6, 7, and 8 (MAZ) and St. 10 (DZ) showed quality improvement only during the winter period (Figure 6C). Both spatial and temporal differences in the M-AMBI scores of the BFZ (ANOVA *F*=9.2, P <0.001) and the MAZ were significant (*F*=.3, P=0.04).

Relationship between the estuarine environment and macrobenthos

The Pearson's correlation coefficients indicate a significant relationship between water quality parameters and benthic (AMBI

TABLE 3 Result of three-way ANOVA of macrobenthic faunal abundance data (Polychaeta, Mollusca, and Crustacea): Comparing the significance of seasonal, species, station differences, and their interaction effects (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

Group	Source	Degrees of Freedom	Mean Sum of Squares	Snedecor's F ratio	Remarks
Polychaeta	Between seasons (A)	2	72.63	2.38	$p > 0.05$
	Between species (B)	44	159.52	5.23***	$p < 0.001$
	Between stations (C)	11	99.99	3.28**	$p < 0.01$
	AB interaction	88	67.44	2.21**	$p < 0.01$
	BC interaction	484	48.28	1.58**	$p < 0.01$
	AC interaction	22	20.02	0.66	$p > 0.05$
	Error	968	30.52		
Mollusca	Between seasons (A)	2	0.45	7.74**	$p < 0.01$
	Between species (B)	10	0.30	5.14**	$p < 0.01$
	Between stations (C)	11	0.14	2.51**	$p < 0.01$
	AB interaction	20	0.11	1.94**	$p < 0.01$
	BC interaction	110	0.07	1.25*	$p < 0.05$
	AC interaction	22	0.11	1.86**	$p < 0.01$
	Error	220	0.06		
Crustacea	Between seasons (A)	2	1.09	0.14	$p > 0.05$
	Between species (B)	13	87.27	11.07***	$p < 0.001$
	Between stations (C)	11	9.64	1.22	$p > 0.05$
	AB interaction	26	5.15	0.65	$p > 0.05$
	BC interaction	143	10.04	1.27*	$p < 0.05$
	AC interaction	22	10.88	1.38	$p > 0.05$
	Error	286	7.89		

and M-AMBI) indices, whereas sedimentary attributes did not show any marked association (Table 5). Among the water quality parameters, temperature, pH, and salinity were influential in assessing community health. The distribution of macrobenthos in EGI, EGIII, and EGIV seems to have been governed by temperature, pH, salinity, and DO conditions (Table 5).

Discussion

Environmental status of Mahanadi estuary

As physically controlled ecosystems, estuaries are characterized by wide variabilities in their local environmental conditions. The environment, however, becomes imbalanced and stressed when exposed to increased anthropogenic stressors (Kennish, 2005; Brown et al., 2022; Suzzi et al., 2022).

Among the environmental variables observed for the MES, the water temperature was strongly marked by seasonality. In this case, other atmospheric influences, such as precipitation, nearshore sea temperatures, and river run-offs, are likely to influence its variability (Leal Filho et al., 2022). High water temperature in the premonsoon was evident in the present study. The other traceable stressors like municipal wastes, sewage, and litter from Paradip port city, fisher hamlets, and fishing harbour that enter the estuary through Atharbanki, a mangrove channel, are also found to affect the water quality to a greater extent. Nutrient enrichment at the stations close to BFZ, shrimp farms, and the fertilizer industry (Sts. 1-3 and 6-8) can be explained by avifaunal excrements and untreated effluents. The low pH in the proximity of industries (Sts. 8-9) is attributable to the influx of acidic wastes (Sundaray et al., 2009; Acharyya et al., 2021a; Acharyya et al., 2021b). On the other hand, (acidic) humic substances carried by freshwater in colloidal suspension get coagulated upon meeting the seawater and can shift the pH to an alkaline condition (Beer, 1996). The latter was apparent from the downstream measurements at the Mahanadi estuary and was similar to findings from other estuaries elsewhere (Mohanty, 2018; Habib et al., 2021; Jabir et al., 2021).

The east-flowing rivers in India, the Brahmaputra, Ganges, Irrawaddy, Godavari, Mahanadi, Krishna, and Cauvery, contribute significantly to the total freshwater discharge into the Bay of Bengal (BoB) (from 1.5 × 10^{12} m^3 to 1.83 × 10^{13} m^3 per year) (Varkey et al., 1996; Thadathil et al., 2002). These rivers have a maximum climatological discharge between July and September when the southwest monsoon rainfall is at its peak and decreases gradually to a minimum during the winter and premonsoon (Sandeep and Pant, 2019). Hence, salinity with an increasing gradient towards the mouth of the estuary was low for the wet (monsoon) season and high for the dry (winter) season. Higher DO at Sts. 5-7 of the MAZ could be due to

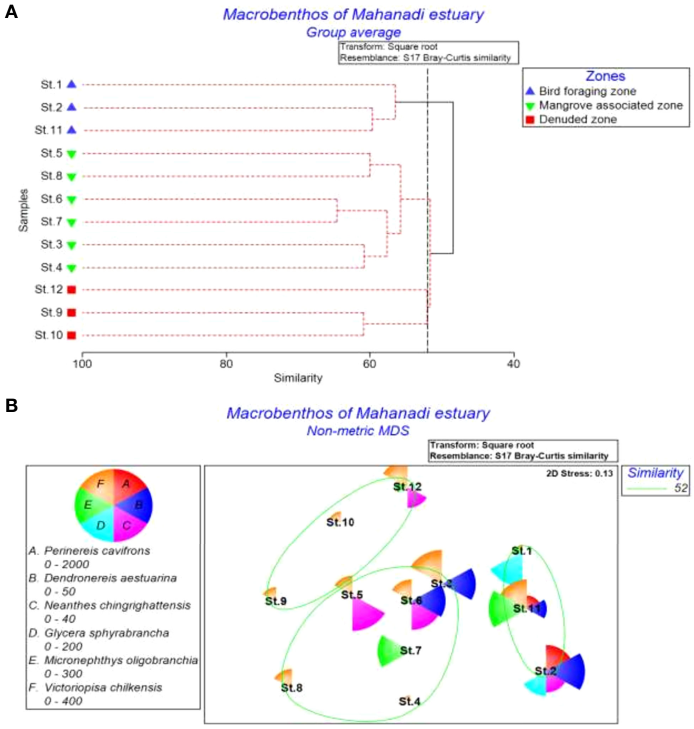

FIGURE 4

(A) Bray-Curtis similarity and **(B)** n-MDS ordination showing sampling (1-12) site groupings based on macrobenthic abundance data in the Mahanadi estuary (similarity: 48.7%).

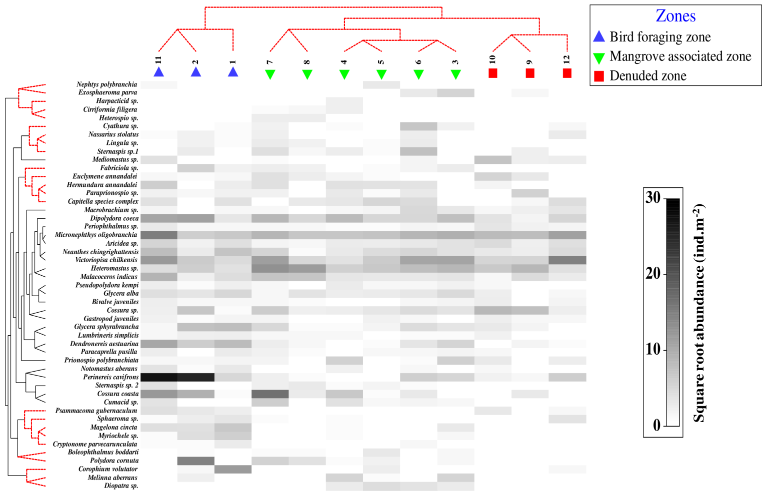

FIGURE 5

Macrobenthic communities of Mahanadi estuary in 2013-2017: Shade plot, a visual representation of abundances (averaged over seasons) of 49 macrobenthic species accounting for ≥ 1% or ˜1% of the total abundance at one or more sampling sites. Groups are named Bird foraging zone, Mangrove associated zone, and Denuded zone with linear greyscale intensity proportional to square root transformation abundance (ind.m^{-2}). The three significantly different sub-clusters marked by SIMPROF-powered UNCTREE analysis (X-axis) are evident.

sustained autotrophic production in the waters. This process originates through nutrient-rich outwelling from the adjacent mangroves during inundation regimes (Cohen et al., 2004; Prasad and Ramanathan, 2008). However, land-based sulphate leaching from the gypsum dumps (heaped close to the fertilizer industry), and industrial effluents, besides others, are the drivers of near hypoxia conditions at Sts. 8-10 (cf. Nayak et al., 2018; Taillardat et al., 2020; Sharma et al., 2022). Depletion in DO is a strong indicator of poor water quality (Costa et al., 2018). Such low DO can prolong hypoxia and affect major estuarine ecosystem-level processes, including fluxes and rates linked to carbon and nitrogen biogeochemical cycling. Therefore, maintaining the best possible conditions across the river basins, including coastal and offshore waters, is essential (Karydis and Kitsiou, 2013; Barletta et al., 2019) and crucial for ecosystem functioning and maintaining estuarine biodiversity (Ghosh et al., 2022).

Fine sediment deposition is difficult in the regions where strong water currents persist (Mitchell, 2020). Low fine particle accretion, sandy texture, and lesser OM at seaward (St. 1) and near confluence sites (Sts. 10, 12) support this phenomenon in the study area. Similarly, mud (silt and clay) accruals occurred mainly in sheltered seascapes (mangrove-fringed sites, Sts. 3-8) due to weak tidal currents and land-based fine particle sources. Muddy sediments retained more OM (>2%) than sandy sediments because of the better adsorption capacity of the fine-grained particles (Gaonkar et al., 2021; Haddout et al., 2022). Furthermore, litter from mangrove vegetation (leaves, propagules, and twigs) and subsurface root growth significantly deliver organic carbon to mangrove sediments (Alongi, 1998). Therefore, sites adjoining mangroves revealed higher OM arising from autogenic sources and outwelling (Hossain et al., 2014; Mohanty et al., 2019).

Reliable information on aquatic resources is key to improving their management (Karydis and Kitsiou, 2013). Furthermore, the competence in accommodating changes (episodic or permanent) to managerial plans requires an in-depth understanding of the drivers of water quality deviations and the availability of natural resources at different timescales (Costa et al., 2018). Anthropogenic activities have significantly threatened the Mahanadi estuary's water quality and biota. As a result, continuous monitoring and potential corrective measures are required to mitigate such effects.

Macrobenthos of Mahanadi estuary

Studies on the macrobenthos of the MES and adjacent mangrove waterways/intertidal mudflats are confined mainly to taxonomic accounts, without much inference to the local environmental conditions (Deb, 1998; Pattanayak and Haldar, 1998; Rao, 1998; Surya Rao and Maitra, 1998; Nayak et al., 2018; Tudu et al., 2018; Mohanty et al., 2022). In recent years, industrial expansion has become disproportionately rapid along major waterways due to well-connected transport hubs and habitation sites, as is the case for the MES. The complex network of creeks and canals acting as vectors and sink for the effluents released from the port town, fishing harbour/landing centers, industrial units, etc. (Rodgers et al., 2020) shows significant consequences on the benthic communities.

Macrobenthic diversity and dominance patterns in the Mahanadi estuary reflected varying degrees of natural and man-induced stressors. Spatial and temporal benthic faunal distribution appeared to be primarily structured by sediment texture, OM, salinity, and pH. For instance, the abundance of polychaetes in the estuary could represent their tolerance to a wide array of (shifting/changing) environmental conditions (Sanchis et al., 2021). The deposit-feeding *P. cavifrons* is an important link between detritus accumulation and higher trophic levels. As an opportunist, *P. cavifrons* can repopulate in defaunated areas where the perturbations like dredging (St. 2, opposite to fishing harbour) and mangrove denudation (sites in the proximity of industries) occur. Furthermore, the capitellids, including *Heteromastus*, spionids, and *Magelona* spp., exhibit a natural proliferation in fine-muddy sediments (Afli et al., 2008; Sivadas and Ingole, 2016), while *Paraprionospio* and *Magelona* spp. survive in hypoxic and lesser competitive environments inhospitable to their predators and competitors (Sivadas et al., 2021). The impoverished faunal trends noticed towards the estuary mouth (St. 1) and upstream (St.12) also confirm the observations of Shirodkar and Nayak (2010). Macrobenthos in the proximity of shrimp farms and industries (IFFCO, Essar Steel) could represent the impacted environmental conditions as pollution indicators (Borja et al., 2000; Dauvin et al., 2012; Albano et al., 2013; Shivarudrappa et al., 2019). Seasonally varied diversity indices are perceptible, with maximum abundance in the winter (Kundu et al., 2010). The findings of this study were consistent with other regional (Mulik et al., 2017; Dias et al., 2018; Rehitha et al., 2019; Sivadas et al., 2021; Subramanian et al., 2021; Kumar et al., 2022; Rehitha et al., 2022) and global (Abrogueña et al., 2021; Bravo et al., 2021; Dauvin et al., 2021; Salimi et al., 2021; Sánchez-Ovando et al., 2021; Kanhai, 2022) benthic evaluations.

An estuary is a dynamic environment where the macrobenthos are adapted to live in widely shifting environmental conditions over relatively short distances (Ortega et al., 2018). The benthic assemblages of Mahanadi estuary are distinct in relation to the local environmental settings. For example, the heterogeneity in *Micronephtys-Victoriopisa-Heteromastus* assemblage of the MAZ could represent anthropic interventions (through industries, ferry traffic, mangrove destruction, and shrimp farms) modifying the habitat and its preference for the sediment composed of silty-sand and high OM. Also, *Cossura-Dipolydora-Malacoceros* assemblage of the DZ, under similar man-made disturbances (boat berthing, Essar steel), occupied the sediment with silt and

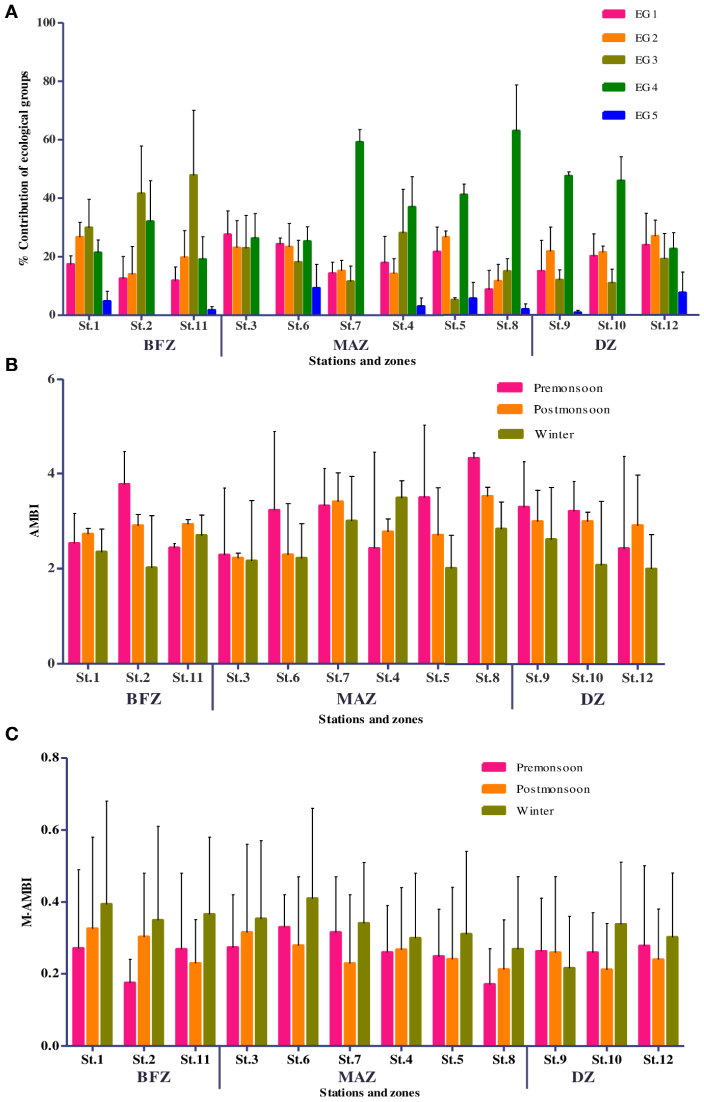

FIGURE 6
(A) Ecological groups associated with stations/zones of Mahanadi estuary; **(B)** AMBI and **(C)** M-AMBI seasonal variations across stations/zones in Mahanadi estuary.

high OM. Therefore, each zone showed the macrofaunal responses to diverse stressors in the vicinity. The effect could be revealed through a low diversity, which testifies to the relationship between biodiversity loss and human-induced disturbances (D'Alessandro, 2020).

Benthic quality status of the Mahanadi estuary

Apart from the anthropogenic interventions, monsoon-mediated perturbations also lead to a high degree of substrate heterogeneity and changes in the structure and function of biological communities in the estuary (Sivadas et al., 2011). The benthic community attributes such as abundance, richness, and diversity fluctuate mostly through defaunation, migration, and spawning of species with recovery followed by stable conditions, recruitment, and resettlement (Gaonkar et al., 2013; Sivadas et al., 2021). As a result, tolerant or opportunist species often dominate these communities, exhibiting a highly dynamic population under specific situations (Sivadas et al., 2016). The health assessment of the MES based on the biotic indices demonstrated a high agreement with inferences extracted from benthic community structures against natural or anthropogenic disturbances.

TABLE 4 Results of AMBI, M-AMBI and biodiversity of macrobenthos from Mahanadi estuary, during February 2013-March 2017.

Stations	EG I (%)	EG II (%)	EG III (%)	EG IV (%)	EG V (%)	Mean AMBI	Disturbance classification (based on AMBI)		N (ind.m^2)	S	H'log$_2$	Mean M-AMBI	Disturbance classification (based on M-AMBI)	
							CHs	EQs					CHs	EQs
St.1	17.98	28.21	26.99	22.46	4.36	2.50	Unbalanced	Good	716.27	12.00	2.84	0.60	Unbalanced	Good
St.2	15.16	17.40	37.29	30.14	0.00	2.74	Unbalanced	Good	1507.18	10.55	1.88	0.48	Polluted	Moderate
St.3	30.25	19.71	22.15	27.59	0.00	2.21	Unbalanced	Good	654.82	9.36	2.36	0.53	Unbalanced	Good
St.4	16.28	15.54	24.05	40.09	4.04	3.02	Unbalanced	Good	430.91	7.55	2.13	0.45	Polluted	Moderate
St.5	24.59	26.14	4.91	39.83	4.55	2.60	Unbalanced	Good	353.64	7.45	2.23	0.47	Polluted	Moderate
St.6	25.02	22.61	20.23	24.27	7.92	2.51	Unbalanced	Good	694.55	11.09	2.44	0.55	Unbalanced	Good
St.7	15.23	15.91	10.18	58.68	0.00	3.18	Unbalanced	Good	1092.18	9.27	2.33	0.48	Polluted	Moderate
St.8	11.08	12.37	15.55	58.44	2.57	3.44	Polluted	Moderate	396.73	6.27	1.93	0.38	Heavily polluted	Poor
St.9	18.66	18.74	11.87	47.97	0.64	2.90	Unbalanced	Good	355.91	6.09	1.81	0.40	Polluted	Moderate
St.10	22.83	22.05	9.93	43.71	0.00	2.64	Unbalanced	Good	430.91	6.82	2.02	0.43	Polluted	Moderate
St.11	12.18	20.16	45.45	20.63	1.56	2.51	Unbalanced	Good	1933.18	10.55	2.02	0.49	Polluted	Moderate
St.12	25.05	28.16	17.27	23.13	6.37	2.36	Unbalanced	Good	573.00	7.73	2.03	0.46	Polluted	Moderate

The mean sample n = 11 at each Station (St. 1 – St. 12).
CHs, Community Health status; EQs, Ecological Quality status; N, Abundance; S, Species richness; H'log$_2$, Shannon-Weiner index.

The dominance of *P. cavifrons, Heteromastus filiformis*, and *Dipolydora coeca* in organically rich and contaminated sediments consequently changed the ecological quality status of MAZ and DZ from *poor* to *moderate*. In contrast, *good* to *moderate* conditions at sandy sediments (BFZ) suggest that low organic content is also favourable to EGI and EGIII forms (Sigamani et al., 2015). Overall, the present study affirms both MAZ and DZ as polluted, with benthic communities of tolerant (EGIII) and second-order opportunistic (EGIV) species. The Odisha Pollution Control Board (OSPCB) estimates untreated domestic wastewater discharge from urban settlements in the Mahanadi basin at 3,45,000 m^3 (m^3 = 1000 liters) per day, producing biochemical oxygen demand (BOD) load of about 68.8 tonnes daily. The water quality index (WQI) of the Paradip coastal waters (riverine and estuarine stretch) also indicated a deteriorating trend from "grade C" in 2013-15 to "grade D" in 2017 (SPCB report card, 2020).

The benthic indices obtained through quality-based evaluation in the present study reflect different stages of the estuarine environmental conditions. Large-scale variability in the environmental parameters and ecological quality status of the benthic habitat at each station (or zone) could be attributable to the heterogeneous MES (Elliott and Quintino, 2007). Temporal variation of macrobenthic communities was evident through either increased or decreased benthic indices depending upon life strategy (r-selected and k-selected) and niche

TABLE 5 Relationship between biotic indices and environmental variables.

Pearsons linear r

Variables	Biomass	N	S	H'(log$_2$)	AMBI	M-AMBI	EGI	EGII	EGIII	EGIV	EGV
Temperature (°C)	-0.323	-0.087	**-0.537****	**-0.448****	**0.475***	**-0.593*****	**-0.439****	-0.156	0.132	0.142	0.221
pH	0.227	0.165	**0.392****	0.304	**-0.643*****	**0.489****	**0.514****	0.19	0.097	-0.534	0.046
Salinity (psu)	0.217	-0.213	0.252	0.213	-0.109	0.264	**0.394***	-0.031	**-0.394***	0.162	0.157
Dissolved Oxygen (mgl^{-1})	0.135	**0.344***	0.121	0.039	-0.261	0.117	0.025	0.099	0.31	**-0.409***	-0.025
Nitrite (μ mol.l^{-1})	0.229	0.164	0.077	-0.133	0.041	-0.034	-0.042	0.094	-0.098	0.101	-0.027
Orthophosphate (μ mol.l^{-1})	0.226	-0.076	-0.084	-0.127	**0.434****	-0.215	-0.29	-0.052	-0.275	0.548	-0.136
Organic matter (%)	-0.121	0.059	0.02	0.012	-0.092	0.042	-0.012	-0.101	0.196	-0.053	-0.299
Sand %	0.171	-0.073	0.207	0.267	-0.176	0.248	0.155	0.314	-0.232	-0.123	0.233
Silt %	-0.171	0.074	-0.206	-0.267	0.175	-0.247	-0.153	-0.314	0.232	0.122	-0.233
Clay %	-0.032	-0.047	-0.153	-0.131	0.219	-0.183	-0.232	-0.05	0.049	0.156	-0.068

Values are Pearson's correlation coefficient; bold font denotes correlations are significant at $p < 0.05$. n = 132.

performance (sensitive, indifferent and tolerant) of the individual species (Equbal et al., 2017). The improved sample quality between premonsoon and winter is suggestive of satisfactory performance by the benthic indices during stable, less turbulent, and low seasonal impact periods (Kröncke and Reiss, 2010; Karakassis et al., 2013; Sigamani et al., 2015; Bae et al., 2016; Chan et al., 2016; Feebarani et al., 2016; Sivadas et al., 2016; Mulik et al., 2017). In fact, for many estuaries on the east coast of India, premonsoon exhibit the most stressed conditions with excess and continuous accumulation of contaminants (Mitra et al., 2018). However, a good flush-out of pollutants is only possible during the monsoon season (Mulik et al., 2020a), aided further by a breakdown of contaminants owing to changing redox chemistry and consequences on benthic-pelagic coupling (Ghosh et al., 2022).

The applied biotic indices evaluated the benthic quality status by discriminating the highly disturbed from the less disturbed areas of the estuary. While the robustness of the M-AMBI (compared to AMBI) in sample quality assessment was explained by several researchers (Khan et al., 2014; Equbal et al., 2017; Pandey et al., 2021), a few others have observed its reverse performance due to lack of reference conditions and spatial benthic variability, heterogeneity within the estuarine complexes (Sigamani et al., 2015). According to Borja and Tunberg (2011), both AMBI and M-AMBI are sensitive to detecting human-mediated disturbances modified by natural disturbances. However, for regions strongly influenced by season, coastal dynamics, and anthropogenic disturbances, the univariate AMBI could show a high degree of variability than the multimetric M-AMBI (Kröncke and Reiss, 2010). The temporal variability of AMBI was indeed found to be less than M-AMBI (Equbal et al., 2018). Nevertheless, the marine biotic index, especially the M-AMBI, appeared to be more robust and realistic in grading the habitat quality into different classes. Therefore M-AMBI index can be used as far as the assessment of benthic habitat quality of the MES is concerned.

Recommendations for conservation and management

Considering the Mahanadi estuary's polluted health status, some holistic management initiatives are required immediately. The government can enforce authority and share responsibilities with local stakeholders, academic institutions, and non-governmental organizations as partners (Romañach et al., 2018). Regular monitoring of the environmental conditions and mangrove cover through advanced research (by observing heavy metal concentrations, application of Remote Sensing and GIS, and others) and citizen science approaches are essential (Zauki et al., 2019; Wolswijk et al., 2020; Durango-Cordero et al., 2021; Gopalakrishnan et al., 2021; Wolswijk et al., 2022). Afforestation of degraded mangrove zones, embankment of tidal rivers - without affecting zonation/succession of the wetland species, and biodiversity conservation (as mandated by the Department of Forest and Environment, Government of Odisha) are some crucial endeavours in the right direction. Moreover, the impact of local pollution on human health should be apprised through appropriate awareness campaigns. The approaches of this kind would be able to lessen the present-day waste discharge, habitat fragmentation, and ecological functioning damages.

Conclusions

The present study unveiled the macrobenthic community of the mangrove-associated MES and demonstrated the impacts of anthropogenic intervention through an ecological approach. Significant sources of anthropic stressors (municipal wastes, sewage, litter, acidic discharges from industries, nutrients, and shrimp farm run-offs) were influential in structuring the macrobenthic assemblages of the MES on spatial and temporal scales. The dominance of opportunistic (second-order opportunists, EGIV) and tolerant (EGIII) species marked the signs of environmental stress, regardless of the sources of disturbance, i.e., natural or anthropogenic. The higher (mean) abundance of opportunists and tolerant species in the MAZ and DZ was mainly caused by OM enrichment that was further modified by the industrial and shrimp farming effluents. Marine biotic indices, especially the M-AMBI, informed the MES's current state of ecological quality. The improved benthic community health from *moderate* to *good* in the premonsoon and winter was largely due to stable environmental conditions, allowing multiple species to co-exist in the light of reduced tolerant/opportunist species. The findings of this study also identified a set of environmental factors (water temperature, nutrient enrichment, salinity, DO, pH) influencing the macrobenthic assemblages of the MES. Evaluating the structure of macrobenthos in relation to anthropogenic/natural pressures and impacts provided the much-needed breadth of knowledge to help the management authorities formulate appropriate conservation strategies/policies. Given the importance of aquatic ecosystems for livelihood and climate change mitigation, the coastal and estuarine ecosystems must be protected so that their goods and services are sustainably utilized in the present and also availed by future generations.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding authors.

Author contributions

AN: Methodology, Field Investigation, Laboratory analysis, Data curation. JE: Software, Data curation, writing. SS: Field Investigation, Laboratory analysis, Figures. BD: Field Investigation, Laboratory analysis, Figures. GT: Software validation, manuscript preparation. DR: Conceptualization, Original draft preparation, and writing. BS: review and editing. PB: review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmars.2022.1008912/full#supplementary-material

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