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International Journal for Modern Trends in Science and Technology
Volume 12, Issue 02, pages 22-29.
ISSN: 2455-3778 online
Available online at: http://www.ijmtst.com/vol12issue02.html
DOI: https://doi.org/10.5281/zenodo.18509297

Benthic meiofaunal distribution and diversity in Uppanar and Vellar estuaries, Southeast coast of India

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To Cite this Article
Seetharaman Sathiyapriya, Perumal Murugesan, Ramchandran Kumaran & Baskaran Vignesh (2026). Benthic meiofaunal distribution and diversity in Uppanar and Vellar estuaries, Southeast coast of India. International Journal for Modern Trends in Science and Technology, 12(02), 22-29. https://doi.org/10.5281/zenodo.18509297

Article Info
Received: 05 December 2025; Revised: 28 December 2025; Accepted: 02 January 2026.

KEYWORDS
Meiofaunal, Density, Diversity, Estuaries, Uppanar, Vellar

ABSTRACT
In the present study, the ecological health conditions of Uppanar and Vellar estuaries and coastal waters was studied by using meiofaunal as a veritable tool. A total of 39 meio-benthic species belonging to four meiofaunal taxa foraminifera, nematodes, ostracodes and harpacticoids were recorded with maximum density of meiofauna (296Nos/10cm3) in Vellar estuary. Among the four meiofaunal taxa, nematodes topped the list with 18 species followed by foraminiferans (14 species), ostracodes (4 species) and harpacticoids (3 species). Comparing different estuaries stations, the maximum number of meio-faunal species (29 species) was recorded in Vellar estuary during summer and minimum (18 species) in Uppanar estuary during monsoon. The maximum meiofauna species diversity was recorded (H') 3.743 at Vellar coastal stations, similarly the maximum species richness (d) 6.879 was recorded at Uppanar estuarine stations and maximum species evenness (J') 0.957 was recorded at Vellar estuary stations. The results of present study helps to develop an understanding on the meiofaunal distribution based on physico-chemical parameters, which will form a reliable tool in bio-monitoring studies.

1. INTRODUCTION

Estuaries serve as vital ecological transition zones between terrestrial and marine environments and play a crucial role in supporting economic development, transportation, fisheries, and human settlements. Nearly 60% of the world's population resides along coastal and estuarine regions, emphasizing their socio-economic and ecological significance (Lindeboom, 2002). Estuaries are partially enclosed coastal water bodies where freshwater from rivers mixes with saline marine waters, creating highly dynamic and productive ecosystems (Mikhailova, 2011; Raj *et al.*, 2019). These systems are characterized by strong physicochemical gradients influenced by tidal exchange, freshwater inflow, sediment dynamics, and geomorphology, making them among the most biologically productive environments on Earth (Elliott and Whitfield, 2011; Day *et al*., 2021).

However, estuarine ecosystems are increasingly subjected to anthropogenic pressures such as industrial effluents, urbanization, dam construction, dredging, aquaculture, and tourism activities, which significantly alter sediment characteristics and biological communities (Allen *et al*., 2012; Kennish, 2019; Pérez-Ruzafa *et al*., 2020). These disturbances influence benthic habitat structure, organic matter availability, and oxygen dynamics, thereby affecting benthic fauna distribution and ecosystem functioning.

Benthic organisms play a fundamental role in estuarine food webs by facilitating organic matter decomposition, nutrient recycling, and energy transfer to higher trophic levels. Meiofauna, comprising metazoans such as nematodes, copepods, ostracods, gastrotrichs, and protozoans including foraminiferans and ciliates, inhabit interstitial sediment spaces and occur across all sediment types and climatic zones (Zeppilli *et al*., 2018; Sergeeva *et al*., 2017). Owing to their high abundance, short life cycles, and sensitivity to environmental fluctuations, meiofauna contribute significantly to benthic productivity and biogeochemical cycling (Giere, 2009; Schratzberger and Ingels, 2018).

The distribution, abundance, and diversity of meiofaunal communities are strongly regulated by environmental factors such as sediment grain size, organic matter content, salinity, temperature, dissolved oxygen, hydrodynamic conditions, and food availability (Górska *et al*., 2014; Majdi *et al*., 2017; Semprucci *et al*., 2021). Among meiofaunal groups, nematodes and foraminiferans are widely recognized as reliable bioindicators due to their sensitivity to pollution, hypoxia, and organic enrichment (Harriague *et al*., 2012; Bonaglia *et al*., 2019; Martínez-Crego *et al*., 2020). Their community structure and functional traits provide valuable insights into environmental health and anthropogenic stress in estuarine ecosystems.

In this context, the present study aims to assess the community composition, density, richness, evenness, and diversity of benthic meiofauna in the Uppanar and Vellar estuaries along the southeast coast of India. By examining spatial and seasonal variations in relation to environmental parameters, the study seeks to enhance understanding of meiofaunal ecology and their role as ecological indicators in tropical estuarine ecosystems.

II. MATERIALS AND METHODS

2. 1. Study area

Sediment samples were collected seasonally from the Post-monsoon (January–March 2021) to Monsoon (October–December 2021) at six stations in the Uppanar and Vellar estuaries. Sampling depths ranged from approximately 1.5 to 7 m. A total of 12 sediment samples, each collected in triplicate (~50cm³), were obtained using a Petersen grab sampler from the uppermost 1 cm layer of the sediment. The samples were immediately transferred into clean, sealed plastic bags and preserved in a cold box until further analysis.

Based on their spatial location, the sampling stations were categorized into downstream (UE-1, UE-2, VE-1, VE-2), midstream (UE-3, UE-4, VE-3, VE-4), and upstream (UE-5, UE-6, VE-5, VE-6) regions to assess variations in ecological conditions along the estuarine gradient. The Uppanar estuary is located at the confluence of the Gadilam and Paravanar rivers, which drain into the Bay of Bengal (latitude 11°42′59.69″N; longitude 79°46′32.15″E). This estuary receives municipal and domestic sewage from the old and new town areas of Cuddalore, effluents from coconut-husk retting activities, and industrial discharges from the SIPCOT (Small Industries Promotion Council of Tamil Nadu) industrial complex. The Vellar River (latitude 11°30′10.22″N; longitude 79°46′40.53″E), originating from the Shervarayan Hills of Salem District, flows along the southeast coast of India before joining the estuarine system (Fig. 1).

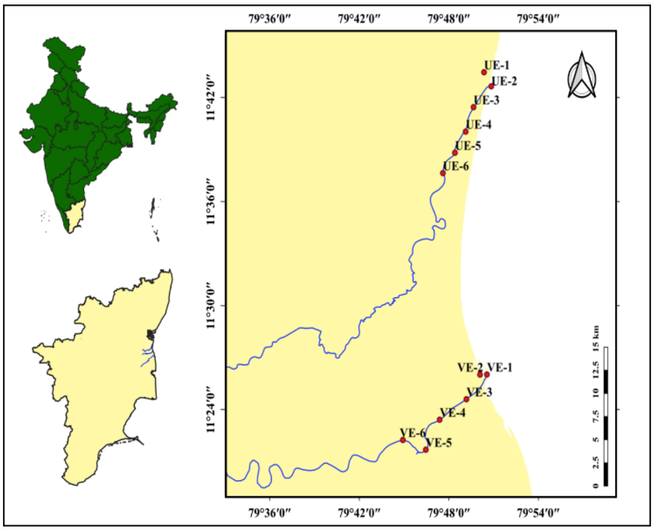

Figure 1. Map showing the sampling stations

2. 2. Collection of Water and sediment samples

The physico-chemical parameters such as Temperature, Salinity and pH were recorded by using the standard instruments (for temperature, Hand held thermometer; Salinity using Hand Refractometer - ATAGO Japan and for pH, the pH pen (model LI-120 Eutech Instrument Singapore) and was estimated using Wingler's method as described by Strickland and Parsons (1972). Water samples were collected by using Niskin water sampler and for the soil nutrients, undisturbed surface sediment samples from the grab haul were collected and shade dried for the Soil texture and Total Organic Carbon (TOC) analysis. The Soil texture analysis was done using pipette method as described by Krumbein and Pettijohn (1938). Total Organic Carbon (TOC) analysis was done by following wet oxidation method of El Wakeel and Riley (1957).

2. 3. Meio-benthos

In each station, three replicate samples were collected using Peterson Grab (biting area 0.1 m^2) by following the method of Mackie (1994). The samples collected were emptied into a plastic tray and then sieved through mesh screen (between 500 and 63µm) as described by Somerfield *et al.* (2018). The sieve retains were preserved in 5-7% formalin and further stained with Rose Bengal solution and the stained samples were left for two days. Subsequently, the meiofauna were sorted, counted and identified into group level and then identified using light microscope (KL-300LED Carl Zeiss microscope) up to lowest possible taxonomic level by consulting the standard works of Loeblich and Tappan (2015); Mohan *et al.* (2013) and Muruganantham *et al.* (2017); Punniyamoorthy *et al*. 2021 for foraminiferans; Chitwood (1958); Chinnadurai and Fernando (2007); Ansari *et al.* (2012) for nematodes; Brouwers *et al*. (2000) and Tanaka (2008) for ostracodes and Boxshall (2001) for Harpacticoids.

2. 4. Data analysis

The data on environmental variables and biological variables were subjected to simple correlation and they were also treated with multivariate methods namely PCA (Pearson Correlation Analysis), CCA (Canonical Correspondence Analysis) and BIO-ENV (Biota-Environment matching using the statistical software PRIMER (Ver.7) (Plymouth Routines In Multivariate Ecological Research, Ver. 7.0; Clarke and Gorley (2015) and Clarke *et al*. (2016). The CCA was done with the software namely PAST (Paleontological Statistics) (Hammer *et al.* 2001).

III. RESULTS

3. 1. Physico-chemical characteristics of water samples

In the present study, the water temperature varied from 25.33 – 30.37°C with minimum at EE-1 during monsoon and maximum at UC-RS during summer; water pH showed minimum of 7.70 at VE-1 during monsoon and maximum of 8.17 at UC-RS during summer; salinity showed a wide range of fluctuation with minimum (4.67ppt) at UE-1 during monsoon and maximum (29.67ppt) at UC-LS during summer. Dissolved oxygen ranged between 5.64 mg/l at UC-LS during monsoon and 3.28 mg/l at EE-2 during summer.

3. 2. Sediment samples

As regards sediment samples, the pH showed minimum (7.81) at UE-1 during monsoon and maximum (8.40) at UC-LS during summer; TOC content varied from 4.15mgC/g at EC-LS during monsoon to 12.8mgC/g at UE-1 during post monsoon. The sand content showed a minimum of 3.67% at EE-1 during monsoon and a maximum of 68.8 % at EC-RS during summer and Clay content varied from 18.00% at EC-LS and a maximum of 72.87% at EE-1 during this study. Cadmium (Cd) concentrations ranged from non-detectable levels (0.42 mg/kg) at VE-6 to a maximum of 3.40 mg/kg at UE-6. Copper (Cu) varied between 4.65 mg/kg at CE-6 and 96.63 mg/kg at UE-6. Chromium (Cr) showed the lowest value at VE-6 (3.70 mg/kg) and the highest at UE-6 (78.38 mg/kg). Lead (Pb) concentrations ranged from 1.09 mg/kg at VE-6 to 5.91 mg/kg at UE-5, while zinc (Zn) exhibited wide variation, with minimum values of 7.66 mg/kg at VE-6 and a maximum of 84.98 mg/kg at UE-6.

3. 3. Meio-benthos

In the present study, as many as 39 species belonging to four groups of Meio-benthic organisms namely Foraminiferans, Nematodes, Ostracodes and Harpacticoids were recorded. Among them, Nematodes topped the list with 18 species. Foraminiferans were found to be the next dominant group in the order of abundance with 14 species. Ostracodes and Harpacticoids came next with 4 and 3 species respectively.

Among the nematodes, *Astomonema jenneri, Daptonema conicum, Draconema cephalatum, Dracograllus chiloensis, Gonionchus arabica, Epsilonema steiner,* *Enoplolaimus abnormis, Greeffiella dasyure, Halalaimus filum, Oxystomina clavicauda, Synonchus glosus, Pandolaimus latilaimus, Neochromadora craspedota* and *Theristus acer* were found to be the common species in the samples collected in various stations. With respect to foraminiferans, *Asterorotalia dentata, Ammonia beccarii, A. tepida, Bolivina limbata, Cornoboides advena, Discorbinella montereyensis, Elphidium advenum, E. texanum, Lagena semistriata, Gaudryina convexa, Globigerina bulloides, Nonion depressulus, Quinqueloculina seminulum, Rosalina globularis, Spirillina limbata* and *Spiroloculina depressa* were found commonly in various stations. The ostracodes species such as, *Basslerites liebaui, Keijella reticulate, Microcytherura nigrescens* and *Neocytherideis senescens* harpacticoids, *Canuella perplexa, Harpacticus chelifer* and *Laophonte thoracica* were found to be common species in the surveyed stations

The population density calculated between the regions varied from 48 to 296nos.10cm^{-3} with maximum was recorded at VE-1 during summer season and minimum at UE-6 during monsoon season (Fig. 2). Seasonally, the maximum number (29 species) of meiofaunal species were recorded during post monsoon in Vellar estuary and minimum (18 species) during monsoon in Uppanar estuary.

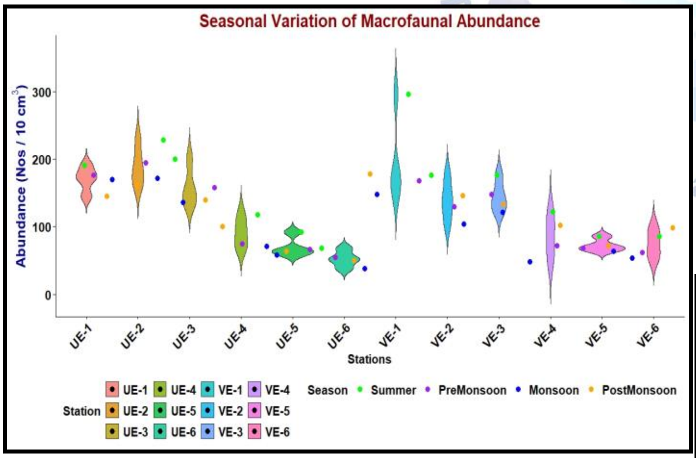

Figure 2. Population density of benthic meiofauna recorded from various stations of Uppanar and Vellar estuaries during the present study

3.4. Percentage contribution

The results of percentage composition of Meio-fauna revealed that Nematodes constituted the maximum with 45% of the total Meio-benthic organisms. Foraminiferans, Harpacticoids and Ostracodes contributed with 30%, 17% and 8% respectively to the total Meio-benthic samples collected in different Station of Vellar estuary (Fig. 3a). Nematodes constituted the maximum with 45% of the total Meio-benthic organisms. Foraminiferans, Ostracodes and Harpacticoids contributed with 36%, 12% and 7% respectively to the total Meio-benthic samples collected in different Station of Uppanar estuary (Fig. 3b).

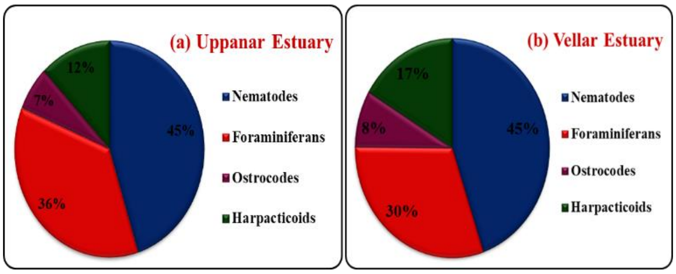

Figure 3. Percentage contribution of foraminiferal orders recorded in various sampling stations of the (a) Vellar and (b) Uppanar estuaries during the present study

3.5. Diversity indices

The Shannon diversity (H′) index calculated for meiofaunal abundance data showed minimum (2.478) value at UE-2 during monsoon and maximum (3.743) value at VE-1 during summer season; Margalef species richness (d) showed minimum (4.528) value at VE-3 during pre-monsoon and maximum (6.879) value at UE-6 in summer; Pielou's species evenness (J') varied between 0.594 and 0.957 with maximum value at VE-1 during summer and minimum value at UE-5 during monsoon and Simpson dominance varied from 0.715 to 0.874 with maximum at VE-1 during Summer season and minimum at UE-3 in monsoon (Table. 1).

Table 1. Diversity indices, a-Shannon diversity (H′); b-Margalef richness (d) c- Pielou's evenness (J′) and d-Simpson dominance (D) calculated for benthic meiofaunal in Uppanar and Vellar estuaries during the present study

Stations ID	Shannon diversity (H')	Margalef richness (d)	Pielou's evenness (J')	Simpson dominance (D)
UE-1	2.494	5.754	0.623	0.812
UE-2	2.478	6.011	0.634	0.869
UE-3	2.788	6.815	0.615	0.715
UE-4	2.592	5.916	0.629	0.835
UE-5	3.122	5.967	0.594	0.791
UE-6	3.193	6.879	0.740	0.807
VE-1	3.743	5.035	0.957	0.874
VE-2	2.983	5.634	0.672	0.744
VE-3	3.436	4.528	0.814	0.726
VE-4	3.252	4.691	0.728	0.805

VE-5	3.176	5.361	0.770	0.718
VE-6	2.855	5.848	0.605	0.872

3.7. Principle component analysis

The PCA plot was drawn to set a well-defined relation between the environmental parameters (DO, temperature, w. pH, salinity, Sand, Silt, Clay, TOC and heavy metals against the surveyed different stations (Fig. 4). The plot revealed that, among the stations, the VE-1, VE-2, VE-3, VE-4, VE-5, VE-6 and UE-2 showed high correlation with parameters such as Salinity, Water pH, TOC, Clay, Sediment pH, water temperature and Sand while UE-1, UE-3, UE-4, UE-5 and UE-6 got highly correlated with other parameters such as silt, Zn, Co, Fe, Cd, Pd and Cr.

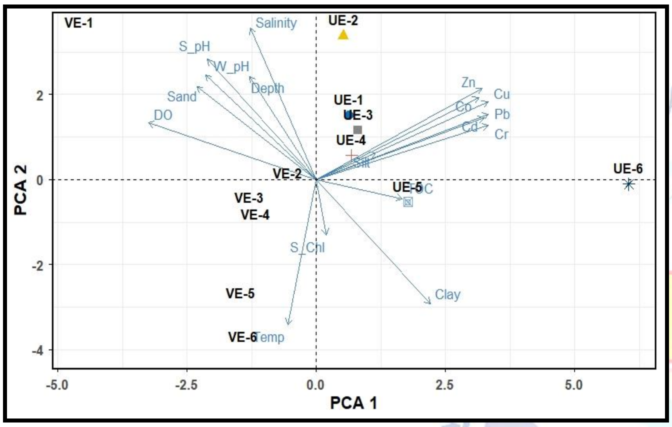

Figure 4. Principle Component Analysis for environmental parameters and Foraminifera species diversity in various stations of Uppanar and Vellar estuaries during the present study

Canonical Correspondence Analysis (CCA) indicated relationships between meiofaunal distributions and environmental gradients in Uppanar and Vellar estuaries. The CCA further revealed that the vectors for most environmental parameters were relatively short, indicating limited variability and influence on the assemblages (Fig. 5). Some species, such as *A. longicauda, H. filum, R. globularis, D. major, M. gracilis, L. macronyx* and *B. liebaui* were positively correlated with temperature, salinity, sandy, soil pH, TOC, and DO at VE-1, VE-2, VE-3, VE-4 VE-5, VE-6. It was also evident that some species (i.e., *A. jenneri, D. conicum, A. beccarii, A. tepida, A. dentata, E. clavatum, E. texanum, S. angulosa, E. acutifrons* and *K. reticulate*) were negatively related to the heavy metals (Cr, Cd, Cu and Pb) at UE-1, UE-2, UE-3, UE-4, UE-5 and UE-6.

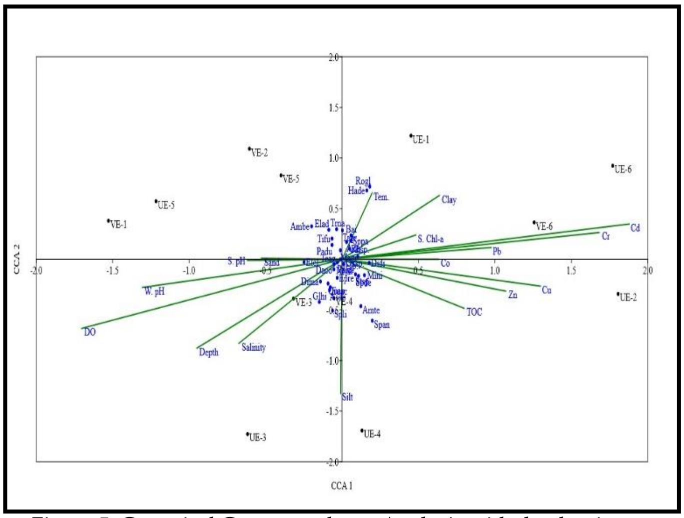

Figure 5. Canonical Correspondence Analysis with the dominant species and environmental parameters for the Uppanar and Vellar estuaries.

IV. DISCUSSION

Estuarine and coastal ecosystems are highly dynamic transitional zones where physicochemical variability, sediment characteristics, and anthropogenic inputs strongly influence benthic community structure. The present study clearly demonstrates that seasonal fluctuations in water quality, sediment composition, and heavy metal concentrations significantly control the distribution and diversity of meiofaunal assemblages in the Uppanar and Vellar estuaries.

Water temperature, salinity, and pH showed marked seasonal variation, with maximum values during summer and minimum during monsoon. Elevated temperature and salinity during summer, particularly at coastal stations (UC-LS, UC-RS, EC-LS, EC-RS), can be attributed to reduced freshwater input, high evaporation, and greater marine influence. Similar seasonal patterns have been reported from tropical estuaries along the Indian coast and elsewhere (Al-Dubai *et al*., 2017; Wang *et al*., 2021; Rao *et al*., 2023).

The decline in dissolved oxygen during summer and post-monsoon seasons may be attributed to increased temperature, enhanced microbial respiration, and organic matter decomposition. Reduced DO in estuarine waters has been widely linked to organic enrichment and restricted water circulation (Amao *et al*., 2019; Kumar *et al*., 2022). The observed values in the present study are comparable with earlier findings from the Uppanar and adjacent estuaries (Nagendra & Reddy, 2019; Saravanan *et al*., 2023).

Sediment texture showed strong spatial variation, with clay and silt dominance in estuarine regions and sandy substrates in coastal areas. The highest TOC values were recorded in fine-grained sediments during post-monsoon, reflecting enhanced terrestrial runoff and organic matter accumulation. Fine sediments are known to act as efficient sinks for organic carbon and pollutants due to their large surface area and adsorption capacity (Rombouts *et al*., 2013; Silva *et al*., 2022). The relationship between TOC and meiofaunal abundance observed in the present study confirms that organic matter availability is a major controlling factor for benthic productivity. Similar observations have been reported in tropical and subtropical estuaries worldwide (Martins *et al*., 2015; Rizzo *et al*., 2021).

Heavy metal concentrations (Fe, Cd, Cr, Pb, and Zn) were significantly higher in estuarine stations compared to coastal sites. This enrichment is primarily associated with industrial discharge, domestic sewage, agricultural runoff, and riverine transport of contaminants. The accumulation of metals in estuarine sediments is further enhanced by fine particle size and organic matter content. Comparable trends have been reported from several Indian estuaries including Ennore, Vellar, and Cauvery systems (Karthikeyan *et al*., 2020). The present findings corroborate earlier reports indicating that estuarine environments act as sinks for heavy metals and are more vulnerable to anthropogenic stress than adjacent coastal waters.

The meiofaunal community was dominated by nematodes, followed by foraminiferans, ostracodes, and harpacticoids. The dominance of nematodes reflects their high adaptability to environmental stress, organic enrichment, and sediment disturbance. Foraminiferans were abundant in relatively stable, saline, and well-oxygenated conditions, particularly in coastal stations. Seasonally, higher species richness and abundance were observed during post-monsoon and summer, while monsoon periods showed reduced diversity due to freshwater influx, sediment resuspension, and fluctuating salinity. Similar seasonal trends have been reported by Pusceddu *et al*. (2014), Khalil (2019), and more recently by Ahmed *et al*. (2022) and Das *et al*. (2024).

Diversity indices (Shannon, Margalef, Pielou's evenness, and Simpson dominance) revealed higher ecological stability at coastal stations, particularly during summer. Lower diversity values at estuarine stations during monsoon indicate environmental stress and habitat disturbance. PCA and CCA analyses clearly demonstrated the influence of salinity, temperature, TOC, sediment texture, and heavy metals on meiofaunal distribution. Stations with higher salinity and sandy substrates supported diverse assemblages, whereas stations with elevated heavy metal concentrations showed reduced diversity and dominance of tolerant species. Similar ecological patterns have been reported by Donnici *et al*. (2012), Fajemila *et al*. (2015), and more recently by Chen *et al*. (2021) and Sigamani *et al*. (2024).

V. CONCLUSION

The present study highlights the strong influence of seasonal variability, sediment characteristics, and anthropogenic inputs on the structure and distribution of meiofaunal communities in the Uppanar and Vellar estuaries. Elevated levels of heavy metals and organic matter in estuarine regions significantly altered meiofaunal composition, resulting in reduced diversity and dominance of pollution-tolerant taxa. The strong correlations observed between meiofaunal distribution and environmental parameters confirm the effectiveness of meiofauna as sensitive bioindicators of ecological health. This study provides updated baseline data for environmental monitoring and management of estuarine ecosystems along the southeast coast of India. The integration of biological indicators with sedimentological and chemical parameters offers a reliable framework for assessing anthropogenic impacts and formulating sustainable coastal management strategies.

Acknowledgements

Authors are grateful to the Director & Dean, CAS in Marine Biology & authorities of Annamalai University for providing necessary facilities. Authors also acknowledge gratefully to the Ministry of Earth Sciences - National Centre for Coastal Research (NCCR) [MoES/NCCR/ME/CAS-MB/53/2017], New Delhi for financial support.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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