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Monsoon-Driven Hydrographic Gradients Shape Seasonal Mesozooplankton Assemblages in the Moheshkhali Channel, a Subtropical Estuary in Bangladesh

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Abstract

Mesozooplankton occupy a critical trophic position in estuarine food webs. However, their seasonal community dynamics and responses to environmental controls remain incompletely resolved in monsoon-driven subtropical estuaries. This study examined seasonal variations in mesozooplankton community composition and their relationships with hydrographic variables in the Moheshkhali Channel of southeastern Bangladesh. Sampling was conducted at five stations across the monsoon, winter, and pre-monsoon seasons using a 200 µm plankton net. A total of 34 mesozooplankton taxa belonging to six phyla were recorded, with copepods dominating across all seasons. Multivariate analyses (NMDS and ANOSIM) revealed significant differences in community composition between monsoon and dry-season assemblages. The monsoon season was characterized by greater contributions of larval and transient taxa, associated with elevated turbidity and temperature. In contrast, winter and pre-monsoon communities were more similar under comparatively stable hydrographic conditions. Exploratory redundancy analysis (RDA) and similarity percentage (SIMPER) identified salinity, turbidity, and temperature as the principal hydrographic drivers of community structure. Seasonal community differentiation was attributable to changes in taxonomic composition, while total abundance and diversity indices remained statistically invariant across seasons. These findings provide mechanistic insights into estuarine mesozooplankton dynamics and offer a baseline for long-term monitoring and management of subtropical estuaries in the Bay of Bengal region.

Keywords: Zooplankton, seasonal variation, community structure, multivariate analysis, Moheshkhali Channel

Introduction

Zooplankton are fundamental in aquatic food webs for transferring energy from primary producers to higher trophic levels [1,2]. Beyond their trophic roles, zooplankton contribute significantly to the biogeochemical cycle through nutrient regeneration and the biological carbon pump [3–5]. Their short life spans and sensitivity to environmental changes also make them effective bioindicators of ecosystem health [6–8].

Mesozooplankton (200–2000 μm) represent the most ecologically influential size class in estuarine and coastal systems among zooplankton [9,10]. Copepods dominate this group but also include meroplanktonic larvae of benthic and nektonic organisms [11]. As the primary consumers of phytoplankton and key prey for fish larvae, mesozooplankton forms a critical trophic link in the pelagic food web [9,10,12]. In addition, they contribute substantially to vertical carbon flux through the production of fecal pellets, molts, and carcasses [10,11,13].

Multiple physicochemical and biological factors shape the mesozooplankton community structure. Temperature influences metabolic and reproductive rates [14]. Salinity regulates osmoregulatory tolerance and species occurrence [15,16]. pH can affect survival and development, particularly for taxa with a calcium carbonate body [17]. Nutrient availability indirectly influences mesozooplankton through bottom-up control mediated by phytoplankton dynamics [18–21]. These drivers act as environmental filters that shape community distribution, abundance, and composition by favoring taxa with specific physiological and life-history traits.

Tropical and subtropical estuaries experience strong seasonal fluctuations in freshwater discharge, turbidity, and nutrient inputs. These fluctuations profoundly affect plankton

productivity and community composition [22]. Bangladesh, located in the northern Bay of Bengal, has an extensive network of estuarine systems. These estuaries experience pronounced seasonality with high freshwater inflow, elevated turbidity, and reduced salinity during the monsoon, while more stable, saline conditions prevail in the dry season (winter/pre-monsoon) [23].

The Moheshkhali Channel is a semi-enclosed system fringed by mangroves and salt marsh vegetation with sandy-muddy substrates supporting diverse benthic and pelagic communities [24]. The channel is an important fishing ground and aquaculture zone that contributes to local livelihoods in the Cox's Bazar region [25]. However, increasing anthropogenic pressures such as aquaculture, industry, and infrastructure development threaten its ecological integrity.

Previous studies in Bangladeshi estuaries have largely focused on taxonomic inventories and abundance patterns of zooplankton [26–35]. For example, Ayshi et al. conducted a baseline taxonomic study on zooplankton in the Moheshkhali Channel [30]. Meanwhile, Abdullah Al et al. applied multivariate analyses to zooplankton communities in the Kutubdia and Kohelia channels [29]. Although valuable, these studies are limited in their integration of multivariate community analyses and hydrographic drivers. Consequently, the mechanisms underlying seasonal community dynamics and environmental filtering in monsoon-driven subtropical estuaries remain incompletely resolved.

The present study aims to address this gap by investigating mesozooplankton community dynamics across monsoon, winter, and pre-monsoon seasons in the Moheshkhali Channel. We examine whether environmental filtering driven by hydrographic gradients explains community structure better than seasonal variation alone. Specifically, we (1)

characterize seasonal changes in community composition at major taxonomic and functional-group levels, (2) identify key hydrological drivers structuring these assemblages using multivariate approaches, and (3) assess the relative importance of seasonal shifts in mesozooplankton assemblage composition relative to changes in abundance or diversity.

Materials and Methods

Study Area

The study was conducted in the Moheshkhali Channel, a semi-enclosed subtropical estuary located along the southeastern coast of Bangladesh and connected to the northern Bay of Bengal (21.4795–21.5036°N, 91.9045–91.9736°E; Fig. 1). The channel is characterized by strong monsoon-driven hydrographic variability and influenced by seasonal freshwater discharge, tidal exchange, and coastal circulation. The system

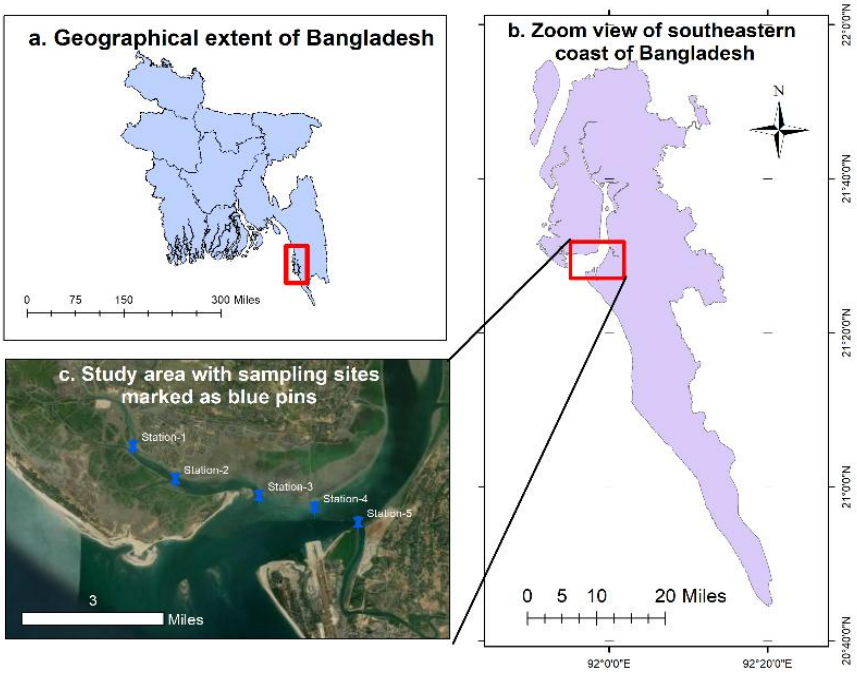


Fig. 1 Geographical location of the study area

experiences higher freshwater inflow, elevated turbidity, and reduced salinity during the southwest monsoon (June–September), whereas comparatively stable and saline conditions prevail during the winter (December–February) and pre-monsoon (March–May) periods (hereafter collectively referred to as the dry season). Mangrove and salt marsh vegetation fringe the channel and support diverse communities. It serves as an important nursery ground and fishing area in the Cox's Bazar region.

Sampling Design

Sampling was conducted during three representative hydroclimatic periods: monsoon (September 2023), winter (February 2024), and pre-monsoon (May 2024). Five sampling stations (Stations 1–5; Fig. 1c) were selected along a longitudinal gradient from more marine-influenced to relatively freshwater-influenced areas. At each station, samples were collected during the daytime (11:00–17:00) at high tide to minimize diel and tidal variability. A total of 15 samples (5 stations × 3 seasons) were collected. However, limited within-season replication is acknowledged as a limitation of the study primarily due to logistical and financial constraints associated with field sampling.

Zooplankton Collection and Preservation

Mesozooplankton were collected using a conical plankton net with a 200 μm mesh size and 0.24 m mouth diameter. Although a 200 μm mesh is standard for mesozooplankton sampling, it may underestimate the abundance and diversity of smaller organisms. Microzooplankton were not sampled due to some fundamental differences in collection and analytical methods. Therefore, the present study focuses only on the mesozooplankton fraction of the zooplankton community. Horizontal surface tows were conducted at 0–0.5 m depth for approximately 1 minute at a towing speed of 1.5–2 m s^{-1}.

The tow distance (100–170 m) were recorded for each sample. The volume of filtered water (V) was calculated as follows:

$$V = \pi r^2 \times d \quad (1)$$

Where *r* is the net radius (0.12 m) and *d* is the tow distance. The estimated filtered volume ranged from approximately 4.5 to 7.5 m³ per tow. Samples were immediately preserved in 4% buffered formalin. Although formalin preservation may affect delicate morphological features in some taxa, it is a widely accepted method for zooplankton studies and supports reliable identification of dominant groups. Potential sampling biases related to net avoidance and organism damage were considered during data interpretation.

Environmental Parameters

In situ measurements of surface water temperature (°C), pH, dissolved oxygen (DO; mg L^{-1}), and conductivity (μS cm^{-1}) were taken using a calibrated multiparameter probe (Lutron WA-2015, Taiwan). Turbidity (NTU) was measured with a portable turbidity meter (Lutron TU-2016, Taiwan). Salinity (ppt) was calculated from conductivity. Water samples for nutrient analysis were filtered through 0.45 μm filters and analyzed spectrophotometrically (UV-Vis, Infitek SP-IUV7) for nitrate (NO_3^-–N), nitrite (NO_2^-–N), phosphate (PO_4^{3-}–P), and silicate (SiO_4^{4-}) following standard methods of Hansen and Koroleff [36]. Nutrient concentrations were expressed in micrograms per liter (μg L^{-1}).

Zooplankton Identification and Enumeration

Zooplankton samples were homogenized and subsampled using a Bogorov counting chamber (80 × 100 mm; 22 mL). Identification and enumeration were conducted under a stereomicroscope (Optica, Italy) equipped with a digital imaging system. Organisms were identified to the lowest possible taxonomic level using regional and standard taxonomic

keys [2,30,37–42]. Species-level specimens were identified when morphological features were clearly distinguishable; otherwise, specimens were classified at the genus level or above. Zooplankton abundance was standardized to individuals per cubic meter (ind m^{-3}) using the following:

$$A = N/V \quad (2)$$

Where *N* is the total number of individuals and *V* is the volume of filtered water.

Diversity and Community Indices

Community structure was evaluated using standard ecological indices: Shannon–Wiener index *H′* [43], Simpson's dominance index *D* [44], Pielou's evenness *J′* [45], Margalef's richness D_{mg} [46]. Using multiple indices reduces the bias of relying on a single metric and allows for a more comprehensive interpretation in responses to hydrographic gradients [47]. The formulas used for these calculations are as follows:

$$Diversity\ H' = -\sum_{i=1}^{s}(P_i)\ln p_i \quad (3)$$

$$Dominance\ D\ = \sum_{i=1}^{s} n_i(n_i - 1)/N(N-1) \quad (4)$$

$$Evenness\ J' = H'/\ln(S) \quad (5)$$

$$Richness\ D_{mg}\ = (s-1)/\ln(N) \quad (6)$$

Where $P_i = n_i/N$ is the proportion of the species *i,* n_i is the count of species *i*, *N* is the total number of individuals, and *S* is the total number of species in the sample.

Data Analysis

Hydrological variables were standardized using z-score normalization. Zooplankton abundance data were Hellinger-transformed for ordination (NMDS and RDA) and square-

root-transformed for similarity-based analyses (ANOSIM and SIMPER) to reduce the influence of rare species and improve species–environment relationships. Seasonal differences in hydrological parameters and diversity indices were assessed using a nonparametric Kruskal–Wallis test due to nonnormality, with significance set at $p < 0.05$. Community patterns were visualized using non-metric multidimensional scaling (NMDS) based on Bray–Curtis dissimilarity. Seasonal differences were tested with analysis of similarities (ANOSIM) and taxa contributing to dissimilarity were identified using similarity percentage (SIMPER) analysis. Relationships between mesozooplankton assemblages and hydrographical variables were explored using redundancy analysis (RDA). Model significance was evaluated using permutation tests. RDA results are interpreted as exploratory due to the small sample size ($n = 15$).

All statistical analyses were performed in R (version 4.5.1) [48] using the vegan package [49], and graphical outputs were generated using *ggplot2* [50].

Results

Mesozooplankton taxonomic composition

A total of 34 mesozooplankton taxa belonging to six phyla and ten classes were recorded (Table 1). Arthropoda dominated the assemblages, primarily through copepods (Calanoida and Cyclopoida). Common calanoid copepods included *Acartia erythraea*, *A. ohtsukai*, *A. tonsa*, *Paracalanus aculeatus*, *Canthocalanus pauper,* and others. Meroplanktonic larvae (decapod zoea, barnacle cypris, and fish larvae) were also present along with mysids, amphipods, chaetognaths, and gastropods. Many taxa were identified only to genus or higher levels due to morphological similarities.

Table 1 Taxonomic classification of mesozooplankton identified in the study area

Phylum	Class	Order	Taxa identified	Major group
Arthropoda	Maxillopoda	Calanoida	*Acartia erythraea* *Acartia ohtsukai* *Acartia tonsa* *Paracalanus aculeatus* *Canthocalanus pauper* *Subeucalanus* sp. *Calanus* sp. *Labidocera* sp. *Centropages* sp.	Copepods
Arthropoda	Maxillopoda	Cyclopoida	*Cyclops* sp. *Oithona* sp. *Oncaea* sp. *Thermocyclops crassus*	Copepods
Arthropoda	Thecostraca	Sessilia	*Balanus cypris* larvae	Cypris larvae
Arthropoda	Malacostraca	Mysida	*Mesopodopsis orientalis* *Mysidopsis* sp.	Mysids
Arthropoda	Malacostraca	Amphipoda	*Gammarus* sp. *Grandidierella megnae* *Ampelisca bocki*	Amphipods
Arthropoda	Malacostraca	Decapoda	*Scylla serrata* *Lucifer hanseni* *Lucifer faxoni* *Penaeus monodon* Decapod larvae (Zoea)	Decapods
Arthropoda	Insecta	Hemiptera	*Micronecta* sp.	Insects
Arthropoda	Branchiopoda	Cladocera	*Evadne tergestina*	Cladocera
Mollusca	Gastropoda	Littorinimorpha	*Rissoa sitta*	Gastropods

			Veliger larvae	
Annelida	Polychaeta	Phyllodocida	Polychaete larvae	Polychaete larvae
Chordata	Actinopterygii	Various orders	Fish larvae	Fish larvae
Cnidaria	Hydrozoa	Narcomedusae	*Linuche unguiculata*	Jellyfish larvae
Chaetognatha	Sagittoidea	Aphragmophora	*Sagitta bedoti* *Sagitta bipunctata* *Spadella cephaloptera*	Chaetognaths

Seasonal dominance patterns

Relative contribution analysis revealed clear seasonal shifts in the dominance structure (Fig. 2). Monsoon assemblages were strongly dominated by a few groups (one group contributing approximately 76%), resulting in a more uneven community than the relatively even distributions observed in winter and pre-monsoon (Figs. 2 and 3).

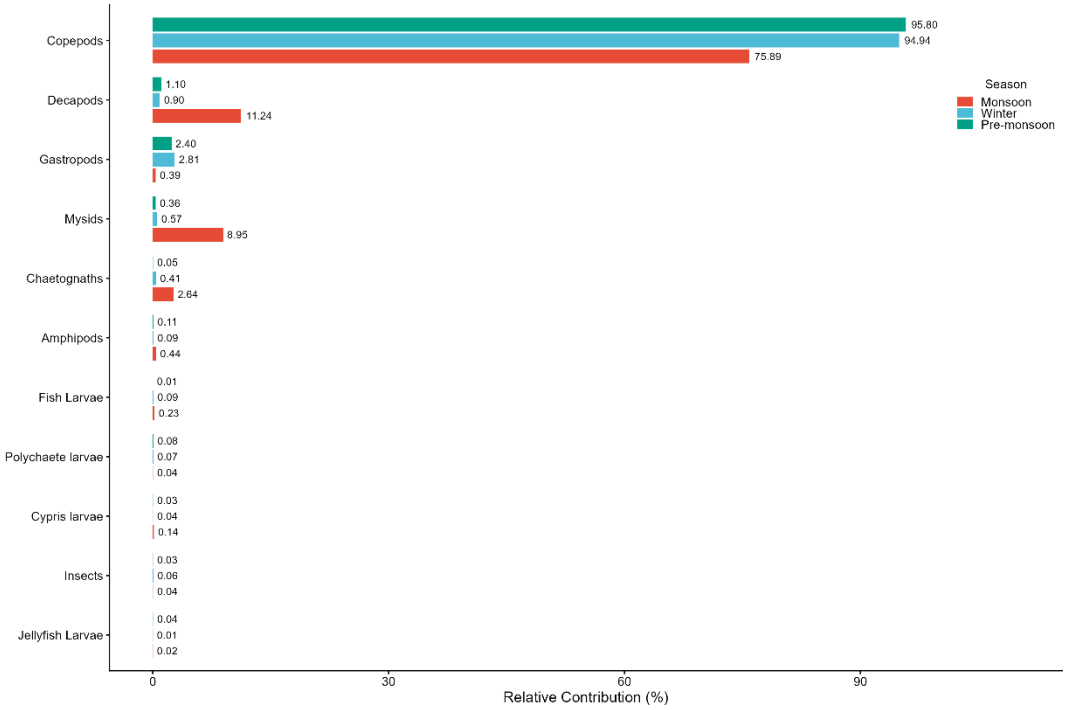


Fig. 2 Relative contribution (%) of dominant mesozooplankton taxa across seasons

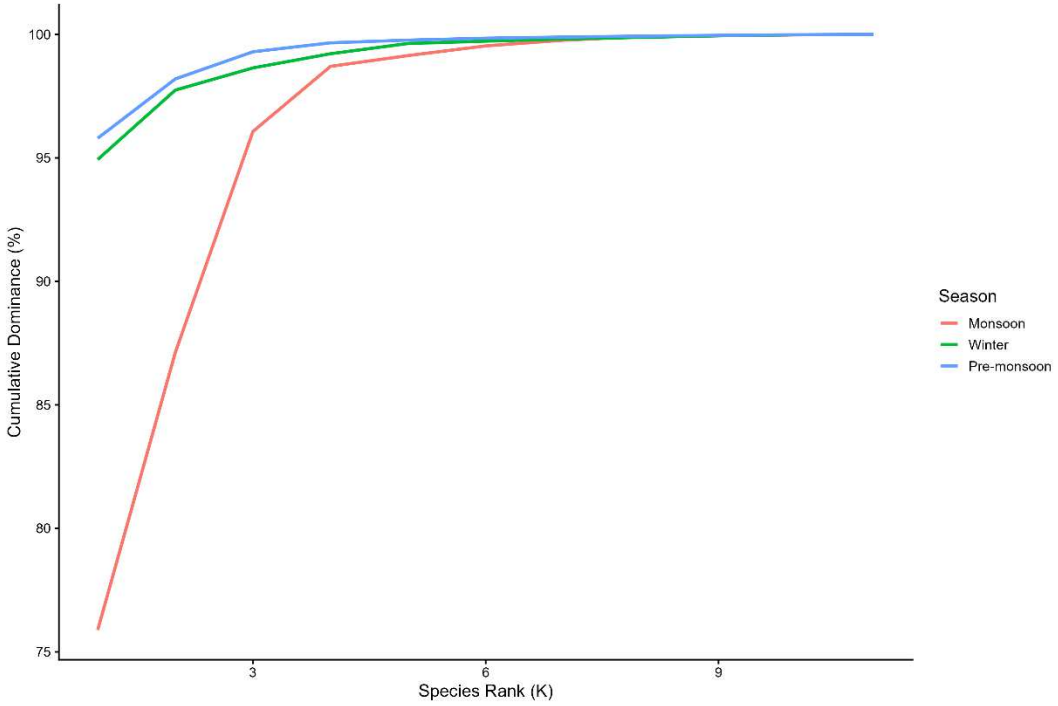


Fig. 3 K-dominance curves showing cumulative dominance (%) by species rank

Seasonal variation in abundance and diversity

Mesozooplankton abundance varied widely but did not differ significantly among seasons (median: monsoon 380 ind m^{-3}, winter 1,846 ind m^{-3}, pre-monsoon 1,163 ind m^{-3}; Kruskal–Wallis, p = 0.20; Fig. 4; Table 2). Shannon–Wiener diversity (H′) was highest during the monsoon (median 0.85) and lower in winter and pre-monsoon (approximately 0.22–0.26), though differences were not statistically significant (p = 0.093). Similar non-significant patterns were observed for evenness, richness, and dominance. The relatively low diversity indices likely reflect strong numerical dominance by a few tolerant or opportunistic taxa and the lumping of rare taxa at higher taxonomic levels.

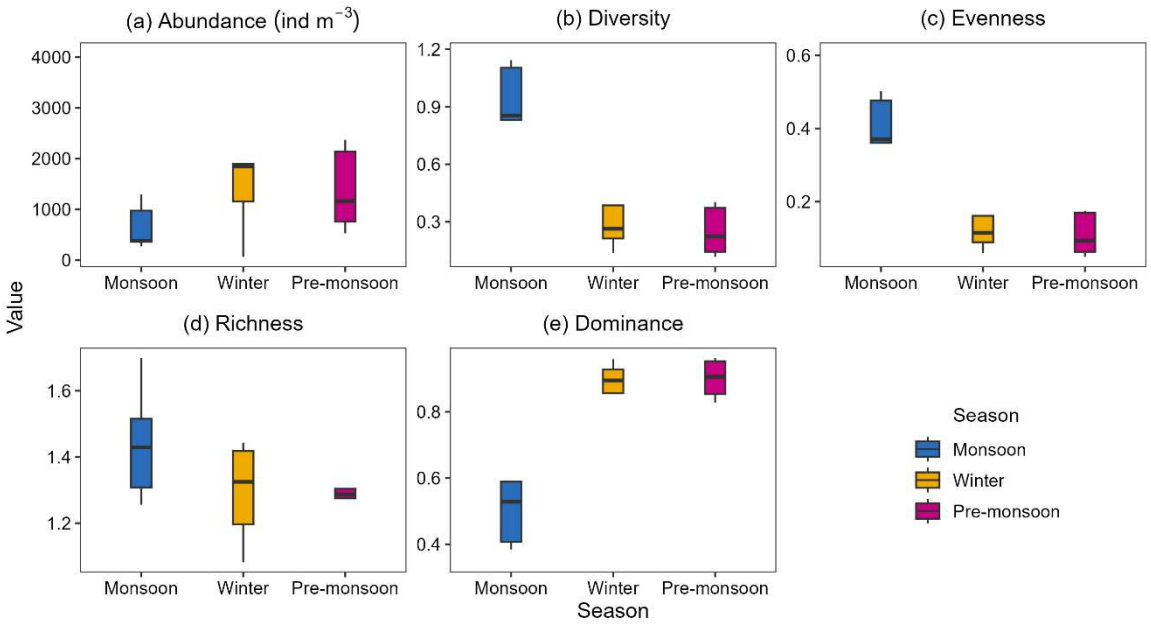


Fig. 4 Seasonal variation in mesozooplankton community indices (abundance, diversity, evenness, richness, and dominance) across the monsoon, winter, and pre-monsoon seasons in the Moheshkhali Channel. Boxplots show medians, interquartile ranges, and outliers

Seasonal variations in environmental patterns

Hydrographic variables showed significant seasonal variation (Fig. 5; Table 2). Salinity increased significantly from the monsoon to winter and remained relatively high during the pre-monsoon ($p = 0.002$). Temperature varied significantly ($p = 0.002$), with lower values in winter and higher values during the pre-monsoon. Turbidity exhibited the strongest seasonal contrast, with markedly elevated values during the monsoon ($p = 0.002$). Dissolved oxygen was highest in winter and lowest in the pre-monsoon, while pH was lowest in winter and highest in the pre-monsoon ($p = 0.006$ and $p = 0.012$, respectively). These patterns reflect highly dynamic hydrographic conditions in the estuary and align with the large-scale seasonal reversal of monsoon currents in the

northern Bay of Bengal. The Southwest Monsoon Current (June–September) enhances freshwater discharge and sediment-laden runoff in the monsoon season. Meanwhile, the Northeast Monsoon Current promotes greater marine influence and more stable, saline conditions during the winter and pre-monsoon seasons.

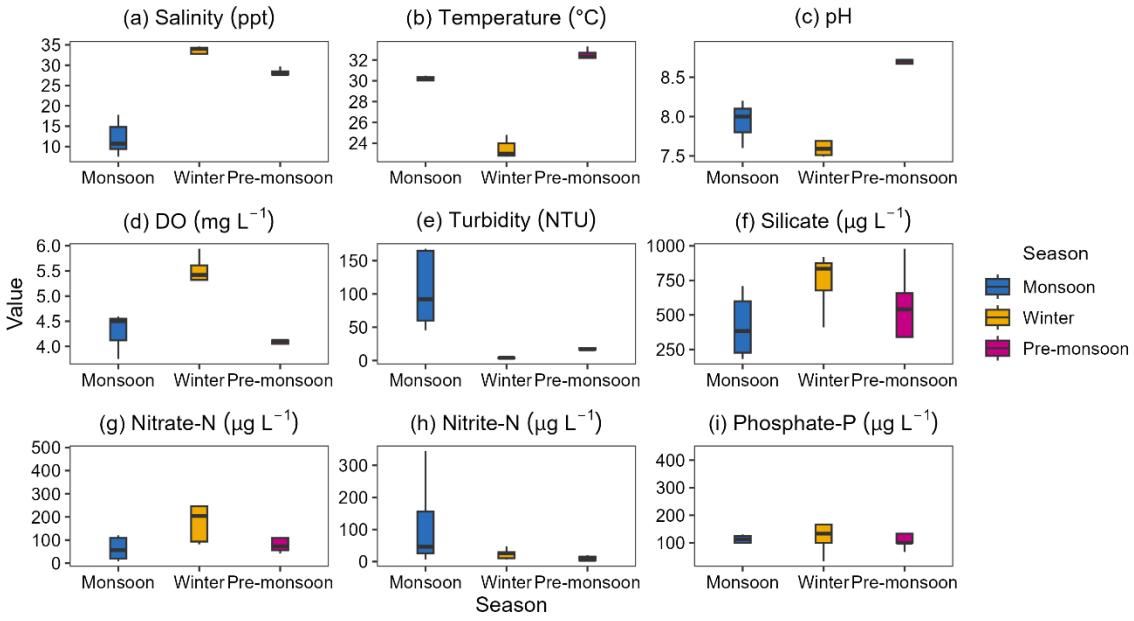


Fig. 5 Seasonal variation in key environmental variables (salinity, temperature, pH, dissolved oxygen (DO), turbidity, silicate, nitrate-N, nitrite-N, and phosphate-P) across the monsoon, winter, and pre-monsoon seasons in the Moheshkhali Channel; boxplots show medians, interquartile ranges, and outliers

Table 2 Summary statistics of mesozooplankton community indices and environmental parameters across monsoon, winter, and pre-monsoon seasons in the Moheshkhali Channel. Kruskal–Wallis rank sum test results indicate the significance of seasonal differences

Variables	Monsoon[1]	Winter[1]	Pre-monsoon[1]	*p*-value[2]
Abundance	379.74 ± 453.51	1,845.95 ± 1,472.63	1,162.50 ± 823.53	0.2
Diversity	0.85 ± 0.34	0.26 ± 0.43	0.22 ± 0.13	0.093
Evenness	0.37 ± 0.15	0.11 ± 0.23	0.09 ± 0.06	0.10
Richness	1.43 ± 0.18	1.32 ± 0.15	1.29 ± 0.08	0.3
Dominance	0.53 ± 0.20	0.89 ± 0.25	0.91 ± 0.06	0.10
Salinity (ppt)	10.70 ± 4.19	34.00 ± 0.90	27.80 ± 0.92	**0.002***
Temperature (°C)	30.21 ± 0.38	23.00 ± 0.91	32.30 ± 1.04	**0.002***
pH	8.00 ± 0.24	7.59 ± 0.25	8.71 ± 0.32	**0.012***
DO (mg L^{-1})	4.50 ± 0.36	5.42 ± 0.48	4.11 ± 0.10	**0.006***
Turbidity (NTU)	92.00 ± 57.65	4.01 ± 0.92	16.92 ± 5.53	**0.002***
Silicate (µg L^{-1})	383.47 ± 229.84	834.37 ± 207.38	540.82 ± 266.50	0.14
Nitrite-N (µg L^{-1})	46.32 ± 140.48	26.30 ± 16.26	5.65 ± 8.29	0.054
Nitrate-N (µg L^{-1})	56.35 ± 50.65	203.86 ± 162.96	73.24 ± 79.36	0.13
Phosphate-P (µg L^{-1})	112.68 ± 14.42	133.33 ± 153.48	100.00 ± 145.04	0.8

[1]Median ± SD; [2]Kruskal-Wallis rank sum test

Community composition patterns

NMDS ordination (stress = 0.049) showed clear seasonal clustering, with monsoon samples distinctly separated from the winter and pre-monsoon samples (Fig. 6). Monsoon samples were characterized by a higher contribution of meroplanktonic and transient groups (e.g., mysids, decapods, fish larvae, amphipods, chaetognaths, and Cypris larvae). In contrast, copepods, polychaete larvae, jellyfish larvae, and gastropods showed higher contributions in the dry-season samples. These patterns were statistically supported by ANOSIM and SIMPER analyses. ANOSIM confirmed significant differences

between monsoon and winter (R = 0.328, p = 0.047) and between monsoon and pre-monsoon (R = 0.428, p = 0.038), but not between winter and pre-monsoon (Table 3). SIMPER analysis indicated that seasonal dissimilarities reflected a broad, community-wide reorganization, with multiple taxa each contributing modestly to the overall compositional shift (Table 4). Copepods consistently contributed the most to dissimilarity, while mysids and gastropods made significant contributions to monsoon-versus-dry-season contrasts.

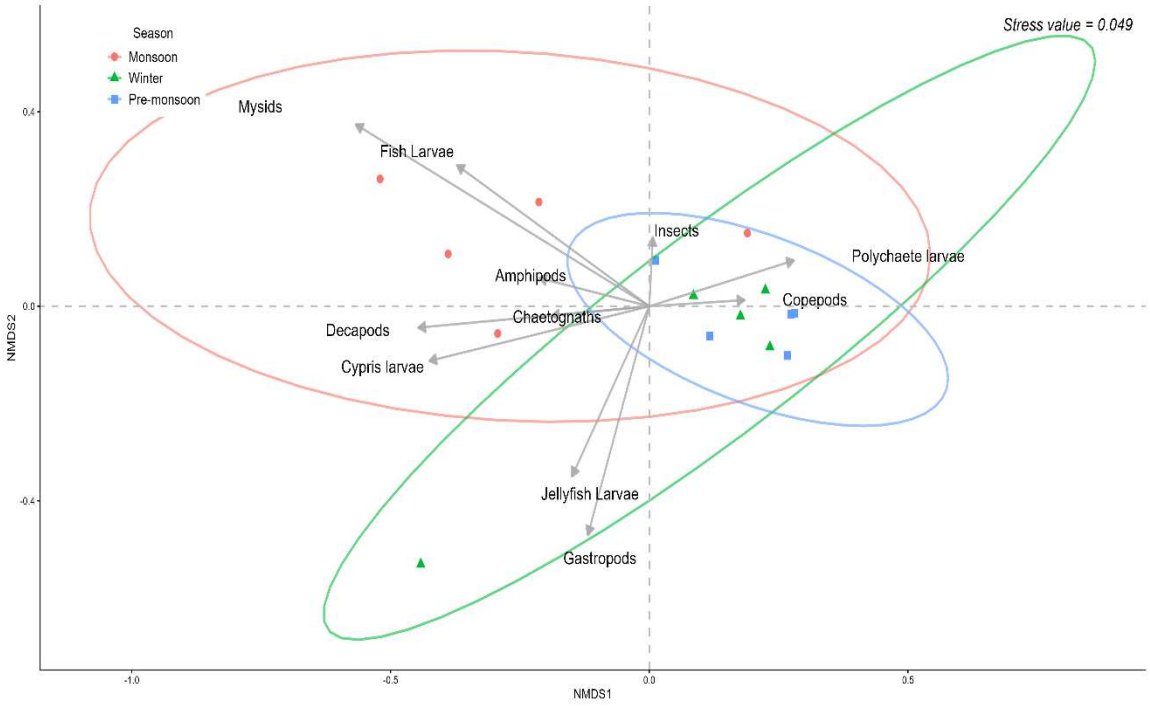


Fig. 6 Non-metric Multidimensional Scaling (NMDS) ordination of mesozooplankton communities based on Bray–Curtis dissimilarity of Hellinger-transformed abundance data. Points are colored and shaped by season; ellipses represent 95% confidence intervals for each season. Species vectors indicate the direction and strength of taxon associations

Table 3 Pairwise Analysis of Similarities (ANOSIM) for differences in mesozooplankton community composition among seasons based on Bray–Curtis dissimilarity. R statistics quantify the degree of separation between groups in ANOSIM, ranging from -1 (within-group dissimilarity greater than between-group dissimilarity) to 1 (complete separation of groups), with R ≈ 0 indicating no difference

Comparison	*R* statistic	*p*-value[1]
Monsoon vs. Winter	0.328	**0.047***
Monsoon vs. Pre-monsoon	0.428	**0.038***
Winter vs. Pre-monsoon	-0.028	0.519

* Indicates Statistical Significance, [1]Permutation test

Table 4 Similarity Percentage (SIMPER) analysis showing the top three mesozooplankton taxa contributing to dissimilarity between seasonal pairs

Comparison	Group	Average Contribution (%)	*p*-value[1]
Monsoon vs. Winter	Copepods	22.4	0.077
	Mysids	5.7	**0.019***
	Gastropods	4.6	**0.039***
Monsoon vs. Pre-monsoon	Copepods	17.3	0.721
	Mysids	5.9	**0.023***
	Decapods	3.9	0.130
Winter vs. Pre-monsoon	Copepods	18.4	0.561
	Gastropods	3.2	0.707
	Mysids	1.9	0.994

* Indicates Statistical Significance, [1]Monte Carlo permutation test

Community patterns were interpreted at the level of major taxonomic groups to reduce uncertainty associated with species-level identification. Although the combination of a 200 µm mesh net and coarser taxonomic resolution may underestimate overall diversity (particularly smaller copepod stages and early larvae), the observed patterns reliably

reflect major seasonal shifts between copepod-dominated assemblages in the dry season and meroplankton-rich assemblages during the monsoon.

Environmental drivers of community composition

Given the small sample size (n = 15), the following RDA results should be interpreted as exploratory rather than confirmatory. Exploratory redundancy analysis (RDA; model R^2 = 0.863) showed that the selected hydrographic variables explained 76.5% of the constrained variation on the first two axes (Fig. 7). Salinity, turbidity, and temperature

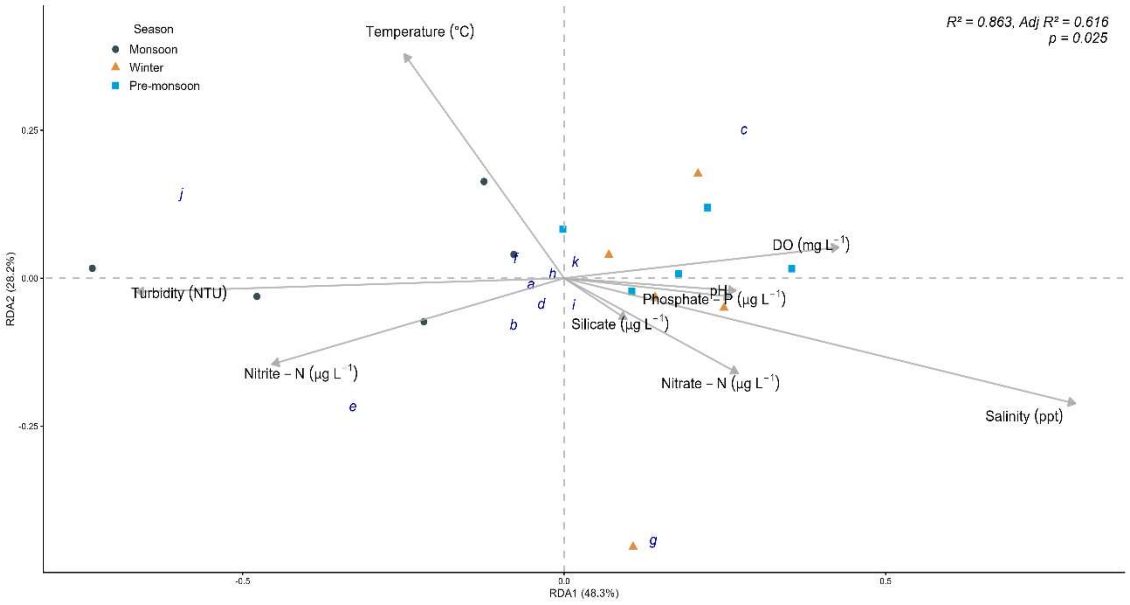


Fig. 7 Redundancy analysis (RDA) triplot showing relationships between mesozooplankton community composition and environmental parameters across three seasons (monsoon, winter, and pre-monsoon). Sampling sites are distinguished by color and shape within each season. Hydrographic variables are shown with arrows, and species scores are labeled with lowercase letters for clarity: (a) Amphipods, (b) Chaetognaths, (c) Copepods, (d) Cypris larvae, (e) Decapods, (f) Fish larvae, (g) Gastropods, (h) Insects, (i) Jellyfish larvae, (j) Mysids, (k) Polychaete larvae

emerged as the strongest variables associated with mesozooplankton community structure. Salinity, dissolved oxygen, and most nutrients were associated with winter/pre-monsoon assemblages dominated by copepods and gastropods. Turbidity and nitrite aligned with monsoon assemblages rich in mysids, decapods, and other meroplankton. While the RDA highlights the dominant role of hydrographic variables, top-down biological controls may also influence mesozooplankton communities. Predation by gelatinous zooplankton (e.g., ctenophores and scyphomedusae) can be important. These biotic interactions were not included in the present model.

Discussion

This study reveals pronounced seasonal variation in mesozooplankton community composition in the Moheshkhali Channel, primarily driven by strong monsoon-induced hydrographic gradients. Salinity increased sharply from monsoon to winter and pre-monsoon seasons due to reduced freshwater input and greater marine intrusion. Turbidity peaked during the monsoon because of high river discharge and sediment resuspension. Dissolved oxygen was highest in winter, while pH reached its maximum during the pre-monsoon period. These local patterns are consistent with the large-scale seasonal reversal of monsoon currents in the northern Bay of Bengal [23].

A total of 34 mesozooplankton taxa were recorded in the present study. This taxonomic richness is consistent with previous investigations conducted in nearby estuarine systems of southeastern Bangladesh (Table 5).

277 **Table 5** Comparative Summary of Zooplankton Studies in Subtropical Estuarine and
278 Coastal Systems of Bangladesh near Moheshkhali Channel

Location	No. of Taxa / Groups	Major Phyla / Groups
Moheshkhali Channel estuarine system	34 taxa (6 phyla, 10 classes)	Copepods (Calanoida, Cyclopoida) are dominant; Gastropods, Mysids, Decapods, and Chaetognaths
Maheshkahli Channel [30]	25 taxa	Copepods are dominant; Mysid shrimps, Shrimp larvae, crab zoea, and ichthyoplankton
Kutubdia channel [33]	38 taxa (22 holo-plankton and 16 mero-plankton)	Copepods, amphipods, shrimps, and mollusks
Kohelia channel and Kutubdia channel [29]	32 taxa (13 orders, 25 families)	*Acartia erythraea, Acetes erythracus, Oithona simplex, Penaeus indicus*
Bakkhali estuary [26]	33 taxa	Copepods are dominant; Mysidaceae and Chaetognaths

279 Although mesozooplankton abundance and univariate diversity indices showed no
280 significant seasonal differences, multivariate analyses (NMDS, ANOSIM, and SIMPER)
281 revealed clear differences in community composition between monsoon and dry-season
282 assemblages. These results indicate that seasonal community dynamics in the
283 Moheshkhali Channel are driven primarily by taxon replacement and not by changes in
284 abundance or diversity. This pattern is consistent with strong environmental filtering along
285 hydrological gradients, particularly salinity and turbidity [51].
286 Copepods (particularly calanoids such as *Acartia* spp., *Calanus* spp., and *Paracalanus*
287 spp.) formed a persistent core community across all seasons, which reflects their
288 euryhaline tolerance, high reproductive rates, and flexible feeding strategies. In contrast,

meroplanktonic and transient taxa, including mysids, decapods, fish larvae, and chaetognaths, were more strongly associated with monsoonal conditions. These groups are likely to benefit from enhanced larval supply and transport during high river discharge, increased nutrient availability through sediment resuspension, and reduced visual predation under high turbidity [52]. Gastropods contributed to dry-season contrasts, consistent with their preference for more stable salinity and higher phytoplankton availability.

Exploratory redundancy analysis (RDA) confirmed that salinity, turbidity, and temperature were the main hydrographic drivers structuring the community. While the present study highlights the dominant role of hydrographic gradients, top-down biological controls, such as predation by gelatinous zooplankton (ctenophores and scyphomedusae), may also be important and can sometimes override physical drivers in the northern Bay of Bengal [53]. Future studies integrating both bottom-up environmental filtering and top-down biotic interactions would provide a more comprehensive understanding of seasonal community dynamics.

The present study advances regional knowledge by applying multivariate ordination techniques to relate seasonal shifts in community composition with environmental filtering. The findings are consistent with previous studies in nearby Bangladeshi estuarine systems but move beyond purely descriptive accounts by emphasizing mechanistic drivers [6,27,52]. Modest ANOSIM R-values and low per-taxon SIMPER contributions further support a model of gradual, multi-taxon reorganization rather than abrupt community replacement.

Mesozooplankton serve as a critical trophic link and nursery resource for commercially important fisheries in the Moheshkhali region. Monsoon-driven larval influxes may represent key recruitment windows, while stable copepod assemblages sustain secondary production during the dry season. These dynamics are vulnerable to ongoing anthropogenic pressures (aquaculture, urbanization, and port development) and climate change (altered monsoon patterns, salinity intrusion, sediment loads). Season-specific monitoring and maintenance of estuarine connectivity are therefore recommended to sustain ecosystem services.

Conclusion

This study demonstrates that mesozooplankton communities in the Moheshkhali Channel exhibit seasonal variation in composition associated with monsoon-driven hydrographic gradients. Although univariate metrics (abundance and diversity indices) showed no significant seasonal differences, multivariate analyses revealed clear shifts in community composition between the monsoon and dry-season assemblages. These changes were driven mainly by the replacement of taxa rather than by shifts in overall abundance or diversity.

Despite limitations in sampling frequency and taxonomic resolution, the present findings provide a valuable baseline for understanding mesozooplankton dynamics in monsoon-influenced subtropical estuaries of the northern Bay of Bengal. Future research incorporating higher-frequency sampling, finer taxonomic resolution, and molecular tools will improve our understanding of trophic linkages and ecosystem responses to climate and anthropogenic pressures.

Limitations and Outlook

The study is based on a single annual cycle with limited replication (n=15), which restricts statistical power and the capture of interannual variability. Surface horizontal tows at high tide provided only snapshots of the community and may have missed vertical or tidal influences. In addition, the use of a 200 µm mesh net and conservative taxonomic identification (many taxa identified only to genus or higher level) likely underestimated total diversity, particularly smaller copepod stages and early larval forms.

Future studies should integrate microzooplankton and phytoplankton data, employ molecular identification methods (e.g., metabarcoding), and conduct multi-year monitoring. Such approaches will strengthen understanding of trophic interactions and help link zooplankton dynamics to fisheries productivity and ecosystem health amid ongoing climate variability and anthropogenic pressures in the Bay of Bengal.

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538

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