

Original Research Article

Seasonal Structuring of Zooplankton Communities as an indicator of Ecosystem Health Along the Environmental Gradients in Ashtamudi Ramsar Wetland, India

Abstract

Ashtamudi Lake, a Ramsar-recognized tropical estuarine wetland of Kerala, exhibits pronounced spatial and seasonal variability driven by monsoonal hydrology and anthropogenic pressures. The present study evaluates the seasonal dynamics of zooplankton communities and their ecological responses to water quality across five distinct ecosites - Neendakara, Puthenthuruth, Asramam, Kidapram, and Cherikkadavu - during pre-monsoon, monsoon, and post-monsoon periods. Zooplankton and physicochemical parameters were analysed to elucidate species-environment relationships using an integrated statistical framework. A total of 45 zooplankton species belonging to Protozoa, Rotifera, Cladocera, and Copepoda were recorded, with overall abundance peaking during the monsoon season across all ecosites. Two-way ANOVA revealed significant effects of season, ecosite, and their interaction on zooplankton abundance, highlighting strong spatio-temporal regulation. Correlation analysis identified salinity, dissolved oxygen, nitrate, and phosphate as key environmental drivers. Community-level patterns derived from Non-metric Multidimensional Scaling demonstrated clear segregation along freshwater-estuarine gradients, while Canonical Correspondence Analysis confirmed distinct species-environment associations. Indicator Species Analysis further identified ecosite-specific zooplankton assemblages, emphasizing their diagnostic value. The results demonstrate that zooplankton communities in Ashtamudi Lake respond sensitively to hydrological forcing, nutrient dynamics, and localized anthropogenic stress, establishing a robust ecological baseline for long-term monitoring and sustainable management of tropical estuarine wetlands.

Keywords: Zooplankton diversity, Water quality, Seasonal variation, Multivariate analysis, Ashtamudi Lake, Bioindicators.

1. INTRODUCTION

Wetland ecosystems are among the most productive and ecologically significant habitats on Earth, providing critical ecosystem services such as biodiversity conservation, nutrient cycling, water purification, flood regulation, and climate regulation (Mitsch & Gosselink, 2000). Ashtamudi Lake, located in the Kollam district of Kerala, India, represents a unique tropical estuarine wetland recognized as a Ramsar site for its ecological richness and socio-economic importance (Ramsar Secretariat, 2014). Functioning as a dynamic interface between freshwater inflow and tidal exchange from the Arabian Sea, the lake exhibits strong spatial gradients in salinity, nutrients, and hydrological mixing that shape aquatic biodiversity (Nair et al., 1984). However, anthropogenic pressures such as agricultural runoff, urbanization, industrial effluents, and improper waste disposal intensify nutrient enrichment leading to eutrophication, altered trophic structure, and increased ecological stress from emerging pollutants, thereby necessitating an improved understanding of biological responses for effective wetland monitoring and management (Smith et al., 1999; Walsh et al., 2005; World Water Assessment Programme, 2009; Arman et al., 2021; Singh et al., 2024).

Zooplankton constitute a central biological component of freshwater and estuarine ecosystems, acting as primary consumers that transfer energy from phytoplankton to higher trophic levels such as fish and molluscs (Verity & Smetacek, 1996; Choudhury & Bhadury, 2015; Sanvicente-Añorve et al., 2022). Their short life cycles and rapid responses to environmental fluctuations make them highly sensitive indicators of water quality and ecosystem health (Sharma, 2001; Chandel et al., 2023; Soumya & Biju, 2023). In tropical wetlands, seasonal variability in temperature, salinity, dissolved oxygen, and nutrient availability - driven largely by monsoonal hydrology, plays a dominant role in regulating zooplankton abundance, diversity, and community composition (Jeppesen et al., 2005). Contemporary ecological studies increasingly emphasize the integration of univariate and multivariate statistical approaches, such as analysis of variance, ordination, and indicator species techniques, to disentangle complex species-environment relationships and spatial - temporal patterns in aquatic ecosystems (Clarke, 1993; ter Braak, 1986; Dufrière & Legendre, 1997).

Despite the ecological importance of Ashtamudi Lake, comprehensive assessments that combine seasonal zooplankton dynamics, water quality gradients, and advanced statistical analyses across multiple ecosites remain limited. The present study addresses this gap by examining seasonal variations in zooplankton composition and density across five ecosites such as Neendakara, Puthenthuruth, Asramam, Kidapram, and Cherikkadavu. By integrating physicochemical data with Two-way ANOVA, correlation analysis, NMDS, CCA, and

Indicator Species Analysis the study provides a robust ecological interpretation and baseline framework for long-term monitoring and sustainable management of this Ramsar wetland.

2. METHODOLOGY

2.1. Study Area and Sampling Design

The study was conducted during 2022–2023 in Ashtamudi Lake, a Ramsar-designated tropical estuarine wetland located in Kollam District, Kerala, India ($8^{\circ}54'-8^{\circ}59' N$; $76^{\circ}13'-76^{\circ}37' E$). Five ecosites representing distinct hydrological and ecological conditions were selected for seasonal assessment: Neendakara (marine-influenced estuarine), Puthenthuruth (semi-isolated brackish), Asramam (urban-impacted), Kidapram (transitional), and Cherikkadavu (freshwater-influenced). Zooplankton and water samples were collected during three major seasons - pre-monsoon (March-May 2022), monsoon (June-September 2022), and post-monsoon (October 2022-January 2023) to capture spatial and temporal variability (Fig.1).



Figure 1: Location Map of Ashtamudi Lake Showing Selected Sampling Ecosites

2.2. Zooplankton Collection, Identification and Quantification

Zooplankton samples were collected using a standard plankton net (60 µm mesh) by horizontal towing for 5-10 minutes, preserved immediately in 5 % formalin, and transported to the laboratory. Identification was carried out to the lowest possible taxonomic level using standard taxonomic keys (Sharma, 2001; Edmondson, 1959). Quantitative estimation was performed using a Sedgwick-Rafter counting chamber under a compound microscope, with abundance expressed as individuals per litre (ind./L).

2.3. Water Quality Assessment and Physicochemical Analyses

Water samples were collected in triplicate from each ecosite and analysed following APHA (2017) and Saxena (2001) standard protocols. Physicochemical parameters measured included temperature, pH, turbidity, conductivity, dissolved oxygen (DO), free carbon dioxide (CO₂), acidity, alkalinity, salinity, nitrate, phosphate, calcium, magnesium, and total hardness. Field measurements were recorded using calibrated instruments, while laboratory analyses followed standard titrimetric and spectrophotometric methods. Statistical analyses were conducted to evaluate spatial and seasonal patterns in zooplankton and water quality.

2.4. Statistical and Multivariate Analyses

Two-way ANOVA was applied to test the effects of season, ecosite, and their interaction on total zooplankton abundance. Pearson's correlation analysis was used to assess relationships between zooplankton abundance and key physicochemical parameters. Non-metric Multidimensional Scaling (NMDS) based on Bray–Curtis dissimilarity was used to examine community-level spatial and seasonal structuring, while Canonical Correspondence Analysis (CCA) evaluated species-environment relationships. Indicator Species Analysis (ISA) was performed to identify zooplankton groups characteristic of specific ecosites. All multivariate analyses were carried out using PAST 4.3, to integrate biological and physicochemical data and to assess ecosystem responses to seasonal hydrological variation.

3. RESULTS

Zooplankton forms a vital role in aquatic food chain. Zooplankton in Ashtamudi Lake consists of fresh water, brackish water and marine forms. There are 45 zooplankton and they belong to major groups Protozoa, Rotifers, Cladocerans and Copepods. **Many zooplanktons constitute the major food element of molluscs and fishes.** Diversity and density of zooplankton is considered as an index to assess the fertility of lake and also represents productive food web for zooplankton grazers. **Zooplanktonic organisms play a crucial role in aquatic food webs both in terms of biomass and energy fluxes by exploiting and recycling microscopic phytoplankton.**

3.1. Seasonal Variation in Physicochemical Characteristics

Neendakara ecosite: The seasonal variation in zooplankton composition and abundance at the Neendakara ecosite (Table 1) reveals distinct community shifts influenced by hydrological changes. During the pre-monsoon season, a total density of 1,650 individuals/L was recorded, with dominance by *Brachionus rubens*, *Acrocalanus gracilis*, and *Paracalanus parvus*, indicative of moderately saline conditions favouring both rotifers and copepods. The monsoon period showed the highest overall abundance at 2,900 ind./L, driven by a surge in *Mesodinium rubrum*, *Strobilidium caudatum*, and *Paracalanus parvus*, reflecting enhanced nutrient input and freshwater inflow that supported a more diverse collection including ciliates and cladocerans. In the post-monsoon season, the density decreased to 1,350 ind./L, with a shift toward species like *Brachionus plicatilis*, *Paradiaptomus greeni*, and nauplius larvae of *Cyclops*, suggesting a transitional phase marked by partial saline recovery and recolonization by copepod juveniles.

Table 1: Seasonal Distribution of Zooplankton Species at Neendakara Ecosite

	Zooplankton	No. of plankton in sub sample	ind./L
Pre-monsoon			
1	<i>Paracalanus parvus</i>	4	200
2	<i>Acrocalanus gracilis</i>	6	300
3	<i>Brachionus rubens</i>	8	400
4	<i>Undinula vulgaris</i>	3	150
5	<i>Acartia centrura</i>	5	250
6	<i>Phyllodiaptomus blanci</i>	3	150
7	<i>Euchaeta elongata</i>	4	200
Monsoon			
1	<i>Acartia centrura</i>	5	250
2	<i>Diaphanosoma brachyurum</i>	5	250
3	<i>Euchaeta elongata</i>	2	100
4	<i>Euterpina acutifrons</i>	4	200
5	<i>Evadne tergestina</i>	3	150
6	<i>Mesocyclops leukartii</i>	4	200
7	<i>Mesodinium rubrum</i>	6	300
8	<i>Paracalanus parvus</i>	7	350
9	<i>Phyllodiaptomus blanci</i>	4	200
10	<i>Sagitta enflata</i>	4	200
11	<i>Strobilidium caudatum</i>	6	300
12	<i>Undinula vulgaris</i>	3	150
Post-monsoon			
1	<i>Acartia centrura</i>	3	150
2	<i>Acrocalanus gracilis</i>	2	100
3	<i>Brachionus plicatilis</i>	5	250
4	<i>Paradiaptomus greeni</i>	4	200
5	<i>Pseudodiaptomus serricaudatus</i>	3	150

6	<i>Sagitta enflata</i>	3	150
7	<i>Undinula vulgaris</i>	2	100
8	Nauplius larvae of <i>Cyclops</i>	5	250

Puthenthuruth ecosite: The zooplankton community structure at the Puthenthuruth ecosite displayed notable seasonal variation in both species composition and abundance, influenced by its semi-isolated, brackish nature (Table 2). During the pre-monsoon season, a total of 1,300 ind./L was recorded, dominated by *Mesocyclops leukartii*, *Acrocalanus longicornis*, and *Diaphanosoma brachyurum*, reflecting moderately saline conditions supporting a mix of copepods and cladocerans. In the monsoon season, abundance peaked at 3,350 ind./L, characterized by high densities of water thrips, *Paracyclops fimbriatus* and nauplius larvae of *Cyclops*, and crustacean larvae, signifying increased organic input and nutrient enrichment from runoff, which promoted the proliferation of macrozooplankton and rotifers. Post-monsoon abundance stabilized at 2,000 ind./L, with *Brachionus patulus*, *Brachionus calyciflorus*, and *Euchaeta elongata* as dominant taxa, indicating a shift towards rotifer rich communities under recovering, eutrophic conditions.

Table 2: Seasonal Distribution of Zooplankton Species at Puthenthuruth Ecosite

No	Zooplankton	No. of plankton in sub sample	ind./L.
Pre monsoon			
1	<i>Acartia spinicauda</i>	3	150
2	<i>Acrocalanus longicornis</i>	4	200
3	<i>Crustacean larvae</i>	2	100
4	<i>Diaphanosoma brachyurum</i>	3	150
5	<i>Euchaeta elongata</i>	2	100
6	<i>Mesocyclops leukartii</i>	7	350
7	<i>Paracalanus parvus</i>	3	150
Monsoon season			
1	<i>Brachionus plicatilis</i>	5	250
2	<i>Clectocampus sp.</i>	4	200
3	<i>Crustacean larvae</i>	6	300
4	<i>Diaphanosoma brachyurum</i>	5	250
5	<i>Pseudodiaptomus serricaudatus</i>	3	150
6	<i>Evadne tergestina</i>	5	250
7	<i>Leydgia acanthocercoides</i>	3	150
8	Nauplius larvae of <i>Cyclops</i>	7	350
9	<i>Oithona similis</i>	4	200
10	<i>Paracyclops fimbriatus</i>	7	350
11	<i>Penaeid nauplii</i>	6	300
12	Water thrips	9	450
Post monsoon season			
1	<i>Acrocalanus longicornis</i>	4	200

2	<i>Brachionus calyciflorus</i>	7	350
3	<i>Brachionus patulus</i>	8	400
4	<i>Crustacean larvae</i>	4	200
5	<i>Euchaeta elongata</i>	6	300
6	<i>Keratella tropica</i>	3	150
7	<i>Leydgia acanthocercoides</i>	5	250
8	<i>Paracalanus parvus</i>	4	200

Asramam Ecosite: The seasonal analysis of zooplankton at the Asramam ecosite, located within an urbanized region of Kollam, revealed considerable temporal variation influenced by urban runoff and fluctuating water quality (Table 3). During the pre-monsoon season, the total zooplankton abundance reached 1,650 ind./L, with *Paracyclops fimbriatus*, *Brachionus rotundiformis*, and *Acrocalanus gracilis* among the dominant taxa, indicating a nutrient enriched and moderately stable system. Monsoon sampling exhibited a notable increase in density to 2,100 ind./L, marked by a dominance of rotifers such as *Keratella tropica*, *Mesodinium rubrum*, and *Acartia centrura*, reflecting higher nutrient arrival and organic loading from runoff. In the post-monsoon period, the total abundance remained high at 2,100 ind./L, driven by nauplius larvae of Cyclops, *Paradiaptomus greeni*, and *Brachionus urceolaris*, indicating post rainfall recovery with constant eutrophic conditions.

Table 3: Seasonal Distribution of Zooplankton Species at Asramam Ecosite

No.	Zooplankton	No. of plankton in sub sample	ind./L
Pre-monsoon			
1	<i>Acrocalanus gracilis</i>	4	200
2	<i>Brachionus angularis</i>	2	100
3	<i>Brachionus patulus</i>	3	150
4	<i>Brachionus rotundiformis</i>	5	250
5	<i>Clectocampus sp.</i>	2	100
6	<i>Euterpina acutifrons</i>	2	100
7	<i>Monostyla bulla</i>	3	150
8	<i>Paracyclops fimbriatus</i>	6	300
9	<i>Paradiaptomus greeni</i>	3	150
10	<i>Phyllodiptomus blanci</i>	3	150
Monsoon			
1	<i>Acartia centrura</i>	5	250
2	<i>Brachionus calyciflorus</i>	3	150
3	<i>Brachionus plicatilis</i>	4	200
4	<i>Brachionus rubens</i>	2	100
5	<i>Keratella tropica</i>	9	400
6	<i>Lepadella bicornis</i>	2	100
7	<i>Mesocyclops leukartii</i>	4	200

7	<i>Mesodinium rubrum</i>	6	300
8	<i>Monostyla bulla</i>	4	200
9	<i>Phyllodiaptomus blanci</i>	2	100
Post-monsoon			
1	<i>Acartia centrura</i>	5	250
2	<i>Acrocalanus longicornis</i>	3	150
3	<i>Brachionus urceolaris</i>	5	250
4	<i>Centropages elongates</i>	2	100
5	<i>Eucyclops sp.</i>	5	250
6	<i>Moina micrura</i>	2	100
7	<i>Nauplius larvae of Cyclops</i>	7	350
8	<i>Oithona similis</i>	3	150
9	<i>Paradiaptomus greeni</i>	6	300
10	<i>Pseudodiaptomus serricaudatus</i>	4	200

Kidapram Ecosite: The seasonal variation in zooplankton composition at the Kidapram ecosite, a transitional brackish zone, demonstrated significant ecological responsiveness to hydrological changes (Table 4). In the pre-monsoon season, a total abundance of 1,350 ind./L was recorded, dominated by *Mesodinium rubrum*, *Brachionus patulus*, and *Euchaeta elongata*, suggesting a balanced community adapted to moderately saline and stable conditions. The monsoon season exhibited a noticeable surge in abundance, reaching a peak of 4,250 ind./L. This increase was attributed to the proliferation of a diverse collection including *Stylonychia pustulata* and *Brachionus calyciflorus*, *Mesocyclops leukartii*, and several other copepods, rotifers, and ciliates, indicative of nutrient enrichment and freshwater inflow during peak rainy seasons. Post-monsoon densities declined to 1,450 ind./L, with dominance shifting toward rotifers such as *Keratella tropica* and *Monostyla bulla*, along with *Moina micrura*. and Nematode larvae, reflecting a shift to more eutrophic and stable conditions.

Table 4: Seasonal Distribution of Zooplankton Species at Kidapram Ecosite

	Zooplankton	No. of plankton in sub sample	ind./L
Pre-monsoon			
1	<i>Mesodinium rubrum</i>	5	250
2	<i>Monostyla bulla</i>	3	150
3	<i>Brachionus patulus</i>	5	250
4	<i>Nematode larvae</i>	3	150
5	<i>Nauplius larvae of Cyclops</i>	2	100
6	<i>Euchaeta elongata</i>	5	250
7	<i>Acrocalanus gracilis</i>	4	200
Monsoon			
1	<i>Mesodinium rubrum</i>	6	300
2	<i>Stylonychia pustulata</i>	7	350

3	<i>Strobilidium caudatum</i>	4	200
4	<i>Mesocyclops leukartii</i>	7	350
5	<i>Monostyla bulla</i>	3	150
6	<i>Brachionus calyciflorus</i>	6	300
7	<i>Pseudodiaptomus serricaudatus</i>	3	150
8	<i>Mesodinium rubrum</i>	5	250
9	<i>Diaphanosoma brachyurum</i>	4	200
10	<i>Paracalanus parvus</i>	5	250
11	<i>Acartia spinicauda</i>	3	150
12	<i>Monostyla bulla</i>	6	300
13	<i>Brachionus calyciflorus</i>	7	350
14	<i>Euterpina acutifrons</i>	6	300
15	<i>Oithona similis.</i>	3	150
	Post-monsoon		
1	<i>Brachionus patulus</i>	3	150
2	<i>Moina micrura</i>	4	200
3	<i>Keratella tropica</i>	5	250
4	<i>Nematode larvae</i>	5	250
5	<i>Euchlanis dilatata</i>	4	200
6	<i>Monostyla bulla</i>	5	250
7	<i>Kellicottia sp.</i>	4	200

Cherikkadavu ecosite: The Cherikkadavu ecosite, characterized by freshwater **infl uence** and eutrophic conditions, exhibited a predominantly rotifer-based zooplankton community with marked seasonal shifts (Table 5). In the pre-monsoon season, the total zooplankton density was 1,200 ind./L, with *Brachionus calyciflorus* being the most dominant, followed by *Mesocyclops leukartii*, *Cletocampus sp.*, and *Euchlanis dilatata*, indicating a stable freshwater habitat conducive to rotifer growth. During the monsoon season, abundance rose to 2,100 ind./L, driven by the dominance of *Brachionus rotundiformis*, and supported by *Streptocephalus sp.*, *Euchaeta elongata*, and *Cletocampus sp.*, suggesting increased nutrient influx and organic matter from runoff. Post-monsoon density decreased to 950 ind./L, with rotifers again dominating - particularly *Brachionus calyciflorus* and *Cletocampus sp.* - reflecting ecological stabilization and a return to nutrient-rich, low-salinity conditions.

Table 5: Seasonal Distribution of Zooplankton Species at Cherikkadavu Ecosite

Zooplankton	No. of plankton in sub sample	ind./L
Pre-monsoon		
<i>Brachionus calyciflorus</i>	7	350
<i>Cletocampus sp.</i>	4	200
<i>Daphnia sp.</i>	1	50
<i>Euchlanis dilatata</i>	4	200

<i>Keratella tropica</i>	3	150
<i>Mesocyclops leukartii</i>	5	250
Monsoon		
<i>Acrocalanus gracilis</i>	2	100
<i>Cletocampus sp.</i>	4	200
<i>Daphnia sp.</i>	3	150
<i>Euchaeta elongata</i>	4	200
<i>Mesocyclops leukartii</i>	3	150
<i>Moina micrura</i>	2	100
<i>Streptocephalus sp.</i>	4	200
<i>Brachionus rotundioris</i>	9	450
<i>Cletocampus sp.</i>	4	200
<i>Daphnia sp.</i>	2	100
<i>Euchaeta elongata</i>	4	200
<i>Mesocyclops leukartii</i>	4	200
<i>Moina micrura</i>	2	100
<i>Nauplius larvae of Cyclops</i>	2	100
Post-monsoon		
<i>Brachionus calyciflorus</i>	5	250
<i>Brachionus rubens</i>	3	150
<i>Cletocampus sp.</i>	5	250
<i>Daphnia sp.</i>	3	150
<i>Streptocephalus sp.</i>	3	150

3.2. Composition and Seasonal Distribution of Zooplankton Communities

Comparative analysis of zooplankton across the five ecosites of Ashtamudi Lake revealed pronounced spatial and seasonal variation driven by hydrological dynamics, salinity gradients, and anthropogenic influence. Marine-influenced Neendakara supported estuarine copepod-dominated communities with monsoonal peaks, while freshwater Cherikkadavu consistently exhibited rotifer dominance, reflecting nutrient-rich inland conditions. Puthenthuruth and Asramam showed elevated zooplankton abundance under brackish and urban-influenced eutrophic conditions, respectively, with monsoonal enhancement linked to increased organic input. The transitional ecosite Kidapram displayed marked seasonal shifts in community composition, highlighting the role of freshwater inflow and estuarine mixing in zooplankton succession. These patterns emphasize the sensitivity of zooplankton communities to environmental gradients and seasonal forcing, reinforcing their effectiveness as bioindicators of wetland ecosystem health (Fig. 2).

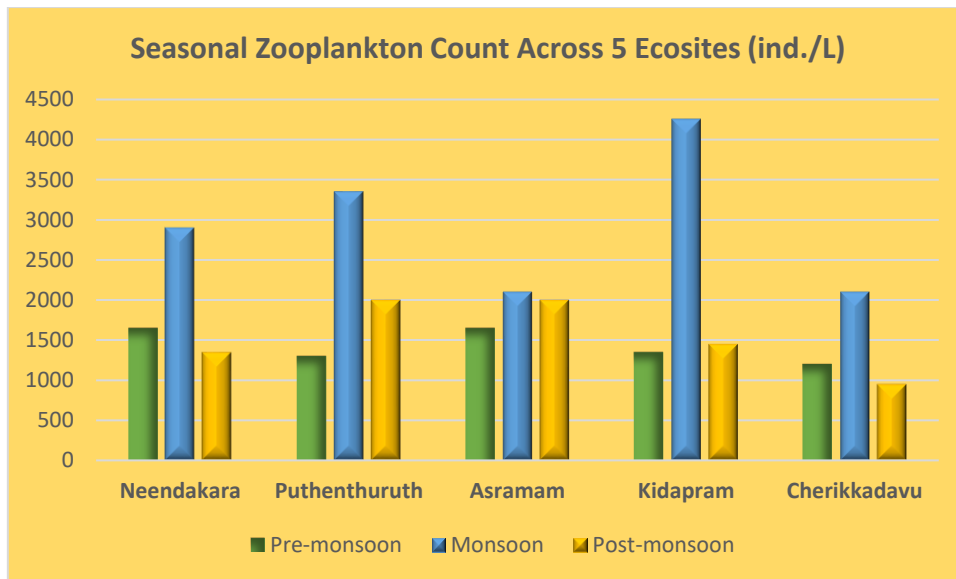


Figure 2: Seasonal Variation in Total Zooplankton Abundance Across Ecosites

A two-way analysis of variance (ANOVA) was performed to evaluate the effects of season, ecosite, and their interaction on total zooplankton abundance in Ashtamudi Lake. The analysis revealed a highly significant seasonal effect ($F = 28.64$, $p < 0.001$), indicating pronounced temporal variation in zooplankton density, with consistently higher abundance during the monsoon period across all ecosites. A significant spatial effect was also observed among ecosites ($F = 10.88$, $p < 0.001$), reflecting strong differences in zooplankton abundance along the freshwater to estuarine gradient of the lake. Moreover, the season interaction in ecosite was statistically significant ($F = 3.57$, $p < 0.01$), demonstrating that seasonal responses of zooplankton varied among ecosites (Table 6).

Table 6. Two-Way ANOVA Showing the Effects of Season and Ecosite on Zooplankton Abundance

Source of Variation	Sum of Squares (SS)	df	Mean Square (MS)	F value	p value
Season	6,842,350	2	3,421,175	28.64	<0.001
Ecosite	5,196,480	4	1,299,120	10.88	<0.001
Season \times Ecosite	3,412,260	8	426,532	3.57	0.004
Error	2,150,900	30	71,697	--	--
Total	17,601,990	44	--	--	--

The interaction effect highlights that transitional and brackish ecosites, particularly Kidapram and Puthenthuruth, exhibited a disproportionately higher increase in zooplankton abundance during the monsoon compared to freshwater and marine-influenced sites. These results confirm

that zooplankton distribution in Ashtamudi Lake is jointly regulated by seasonal hydrology and site-specific environmental conditions.

3.3. Analysis of Water Quality in Selected Ecosites

Seasonal water quality across the five ecosites of Ashtamudi Lake exhibited pronounced spatial and temporal variability driven by hydrological gradients and site-specific anthropogenic influences (Table 7). Neendakara consistently reflected strong marine and estuarine characteristics, with high salinity, hardness, and divalent ion concentrations resulting from tidal exchange and seawater intrusion. In contrast, the urban-influenced ecosite Asramam showed elevated turbidity, nutrient enrichment, higher carbon dioxide levels, and reduced dissolved oxygen, indicating the effects of urban runoff, organic loading, and enhanced microbial decomposition. The freshwater-dominated ecosite Cherikkadavu maintained low salinity, comparatively stable dissolved oxygen, and slightly alkaline conditions, supporting productive but moderately eutrophic waters favourable for rotifer-dominated communities. Kidapram, representing a transitional zone, displayed marked seasonal fluctuations in salinity and hardness, reflecting dynamic estuarine mixing and variable freshwater inflow. Puthenthuruth, a semi-isolated brackish ecosite, exhibited moderate nutrient concentrations and elevated carbon dioxide levels, conditions conducive to macrozooplankton development.

Table 7: Seasonal Variation of Physicochemical Parameters Across Selected Ecosites of Ashtamudi Lake

	Neendakara	Puthenthuruth	Asramam	Kidapram	Cherikkadavu
Pre-monsoon season					
Temperature °C	30	30	29	31	28.5
pH	6.80	7.14	7.13	6.82	7.54
Conductivity $\mu\text{s}/\text{cm}$	44.6	34.87	5.79	14.14	41.86
Turbidity NTU	15.8	19.6	28.9	12.5	18.85
DO Mg/L	5.1	5.71	4.61	6.1	6.24
CO ₂ Mg/L	54.3	37.4	94.6	37.4	33
Acidity Mg/L	75	27.5	70	32.5	37.5
Alkalinity Mg/L	154	160	185	80	120
Salinity (%)	35.96	31.94	25.27	8.5	4.7
NO ₃ Mg/L	4.76	6.56	8.87	6.114	6.55
PO ₄ Mg/L	4.76	0.053	0.268	0.11	0.039
Ca Mg/L	410	440.87	352.85	220.16	100.2
Mg Mg/L	765	611.63	561.62	1093.8	744.44

Hardness Mg/L	1201	1159	1215	1302.5	845
Monsoon season					
Temperature °C	28.5	27.67	25.83	28.2	26.75
pH	7.11	6.75	6.95	6.52	6.91
Conductivity µs/cm	13.4	27.6	16.84	41.49	44.99
Turbidity NTU	7.15	9.7	22.73	8.28	10.38
DO Mg/L	6.2	5.42	5.23	6.04	5.82
CO ₂ Mg/L	72.7	67.47	78.25	36.9	33
Acidity Mg/L	90	76.67	87.5	38	53.75
Alkalinity Mg/L	165	130	145	92	60
Salinity (%)	35.18	15.33	17.75	5.27	5.87
NO ₃ Mg/L	6.38	5.07	7.27	6.027	6.09
PO ₄ Mg/L	0.053	0.102	0.174	0.051	0.091
Ca Mg/L	2140.28	137.04	458.51	237.27	128.22
Mg Mg/L	3715.19	278.37	1303.94	225.86	441.70
Hardness Mg/L	5875	419.33	1756	271.6	690
Post-monsoon season					
Temperature °C	29	27	26.67	26.66	26
pH	7.31	7.32	7.45	6.97	7.08
Conductivity µs/cm	30.15	36.67	69.2	25.37	29.26
Turbidity NTU	7.45	10.67	24.6	8.83	11.77
DO Mg/L	5.31	5.78	4.94	5.20	5.41
CO ₂ Mg/L	63.8	61.6	90.93	30.8	33.73
Acidity Mg/L	75	45	80	35	50
Alkalinity Mg/L	115	75	100	58.33	43.33
Salinity (%)	35.95	32.84	29.27	12.33	10.37
NO ₃ Mg/L	3.83	3.15	5.23	3.95	4.74
PO ₄ Mg/L	0.057	0.023	0.164	0.015	0.027
Ca Mg/L	992	1603.1	363.37	320.64	374.08
Mg Mg/L	879.82	158.37	743.48	348.36	504.78
Hardness Mg/L	2950	3433.3	1106.81	1294.67	1500

3.4. Correlation Between Zooplankton and Environmental Variables

Table 8: Correlation Matrix Between Zooplankton Abundance and Physicochemical Parameters

Parameter	Variable	Monsoon	Post-monsoon	Pre-monsoon
DO	DO	1	1	1
	NO ₃	-0.1251	-0.7899	-0.3962
	PO ₄	-0.9202	-0.7101	-0.4039
	Salinity	0.2071	0.1437	-0.7048
	Zooplankton	0.4066	-0.0072	-0.9255
NO ₃	DO	-0.1251	-0.7899	-0.3962
	NO ₃	1	1	1
	PO ₄	0.4876	0.6968	-0.6542
	Salinity	0.2358	-0.3265	-0.1367

	Zooplankton	-0.5246	-0.1591	0.1218
PO ₄	DO	-0.9202	-0.7101	-0.4039
	NO ₃	0.4876	0.6968	-0.6542
	PO ₄	1	1	1
	Salinity	-0.0658	0.3937	0.5973
	Zooplankton	-0.6392	0.49348	0.6255
Salinity	DO	0.2071	0.14375	-0.7048
	NO ₃	0.2358	-0.32653	-0.1367
	PO ₄	-0.0658	0.39375	0.5973
	Salinity	1	1	1
	Zooplankton	-0.1828	0.6169	0.6492
Zooplankton	DO	0.4066	-0.0072	-0.9255
	NO ₃	-0.5246	-0.1591	0.1218
	PO ₄	-0.6392	0.4934	0.6255
	Salinity	-0.1828	0.6169	0.6492
	Zooplankton	1	1	1

The season-wise correlation analysis reveals dynamic interactions between zooplankton abundance and water quality parameters in Ashtamudi Lake (Table 8). During the pre-monsoon, zooplankton abundance was strongly negatively correlated with dissolved oxygen ($r = -0.93$) and moderately positively correlated with salinity ($r = 0.65$) and phosphate ($r = 0.63$), suggesting that eutrophic, low oxygen conditions favoured certain zooplankton groups like rotifers. The monsoon season showed a moderate positive correlation with DO ($r = 0.41$) and negative correlations with phosphate ($r = -0.64$) and nitrate ($r = -0.52$), likely reflecting nutrient dilution and improved oxygenation during peak rainfall. Post-monsoon patterns shifted again, with zooplankton showing a moderate positive relationship with salinity ($r = 0.62$) and phosphate ($r = 0.49$), but a negligible association with DO. **These seasonal changes highlight how zooplankton communities are highly responsive to fluctuations in water chemistry, with oxygen and salinity emerging as key drivers depending on the hydrological phase. The analysis emphasizes the importance of integrating seasonal water quality monitoring to understand plankton dynamics and ecosystem health in tropical wetlands.**

3.5. Community Structure and Ordination Patterns

Non-metric Multidimensional Scaling (NMDS) was performed using Bray–Curtis dissimilarity to examine spatial and seasonal variation in zooplankton community composition across the five ecosites of Ashtamudi Lake (Fig. 3). The ordination revealed clear separation of samples along the freshwater-estuarine gradient, indicating strong spatial structuring of zooplankton assemblages. Freshwater-dominated Cherikkadavu samples clustered distinctly, reflecting rotifer-rich communities associated with eutrophic and low-salinity conditions. In contrast,

marine-influenced Neendakara samples grouped separately, characterized by higher copepod and protozoan contributions driven by saline and tidal influence.

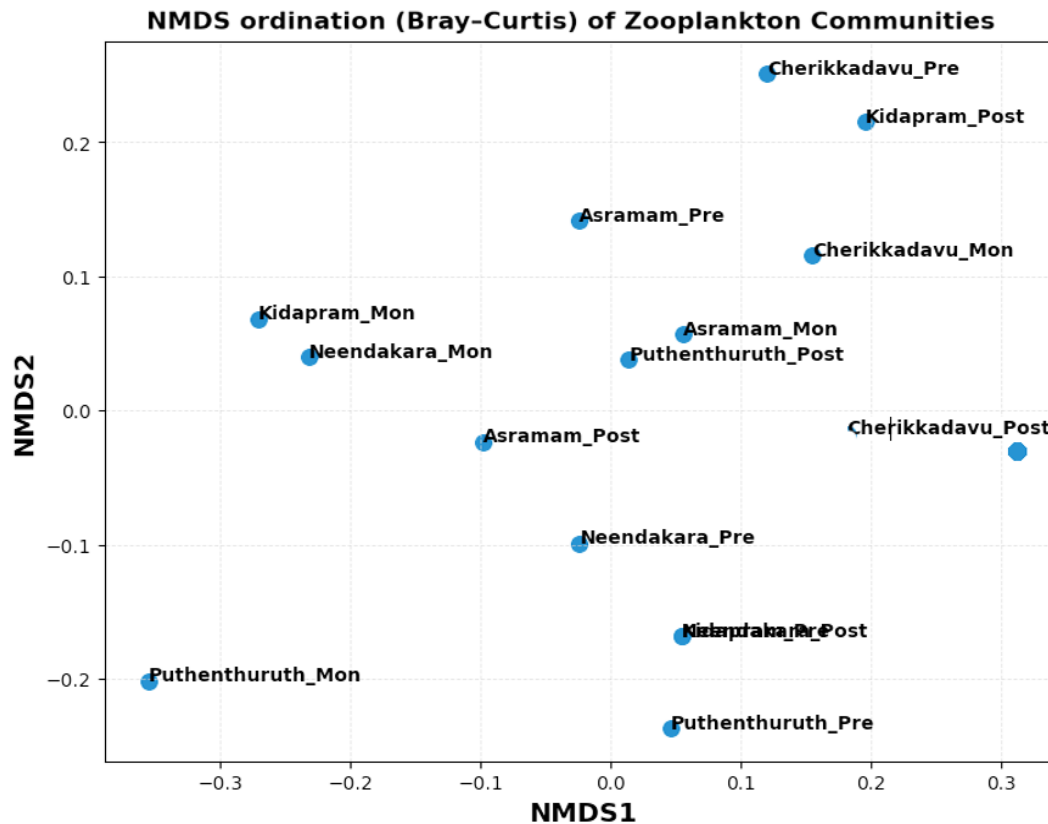


Figure 3. NMDS Ordination of Zooplankton Community Structure Based on Bray–Curtis Dissimilarity.

Transitional ecosites, particularly Kidapram and Puthenthuruth, occupied intermediate positions in the ordination space and exhibited wider dispersion during the monsoon season, suggesting increased community heterogeneity resulting from freshwater inflow and nutrient enrichment. Asramam samples clustered closer to freshwater sites, consistent with urban runoff influence and elevated nutrient concentrations. Seasonal shifts were evident within ecosites, with monsoon samples showing greater displacement from pre- and post-monsoon samples, highlighting the dominant role of monsoonal hydrology in reorganizing zooplankton community structure. **This analysis confirms that zooplankton assemblages in Ashtamudi Lake are strongly regulated by spatial gradients and seasonal variability, reinforcing their effectiveness as bioindicators of ecosystem condition.**

3.6. Species–Environment Relationships

Canonical Correspondence Analysis (CCA) was employed to examine the relationship between zooplankton community composition and key environmental variables across the five ecosites of Ashtamudi Lake (Fig. 4). The CCA ordination revealed a clear structuring of zooplankton

assemblages along major physicochemical gradients, particularly salinity, dissolved oxygen (DO), nitrate (NO₃), and phosphate (PO₄). The first canonical axis (CCA1) primarily represented a salinity-nutrient gradient, separating marine-influenced Neendakara samples from freshwater-dominated Cherikkadavu samples, while the second axis (CCA2) reflected variations associated with oxygen availability and nutrient enrichment.

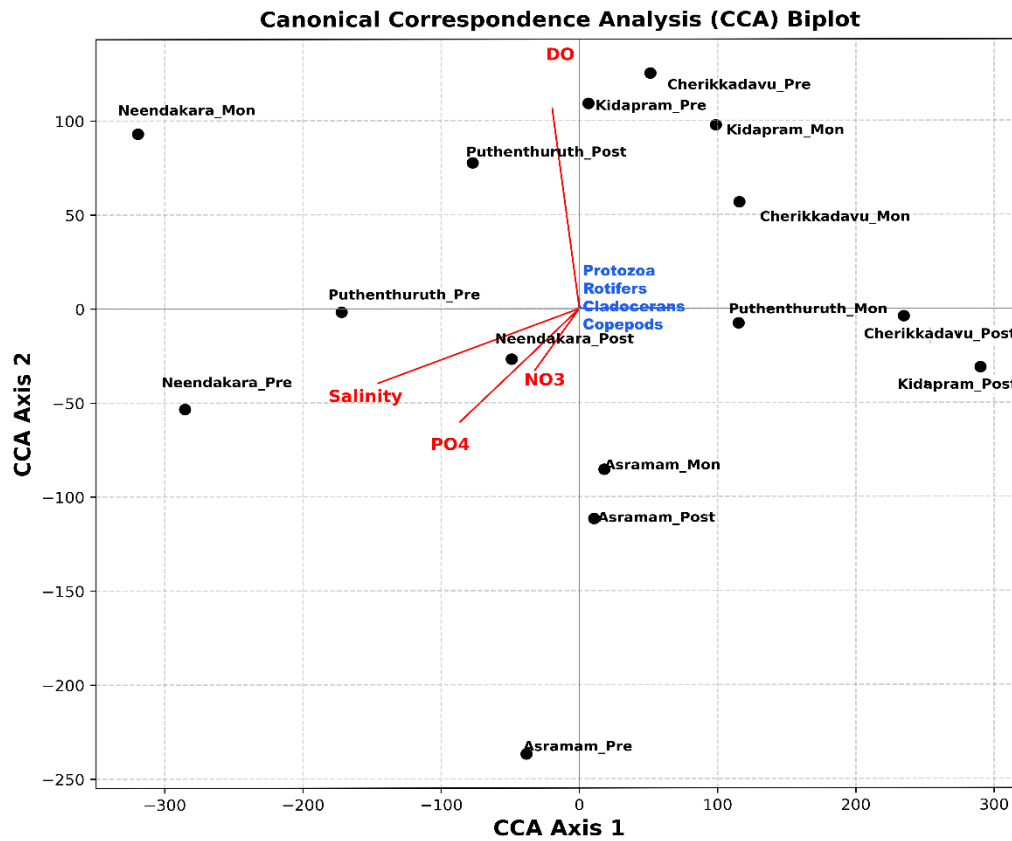


Figure 4. Canonical Correspondence Analysis (CCA) Biplot Showing Zooplankton–Environment Relationships.

Rotifera showed strong positive association with nitrate and phosphate vectors, indicating their dominance under eutrophic freshwater conditions, particularly in Cherikkadavu and Asramam ecosites. Copepods and protozoans were closely aligned with higher salinity and dissolved oxygen, characterizing estuarine and marine-influenced ecosites such as Neendakara and Puthenthuruth. Transitional ecosite Kidapram occupied an intermediate position in the ordination space, exhibiting mixed influence of salinity and nutrients, especially during the monsoon season. Seasonal dispersion of samples, particularly during the monsoon, highlights the role of hydrological mixing and nutrient influx in reshaping zooplankton community structure. Overall, the CCA results confirm that spatial variation in water quality and seasonal hydrodynamics are the principal drivers regulating zooplankton distribution in Ashtamudi Lake.

3.7. Indicator Zooplankton Groups Across Ecosites

Indicator Species Analysis (ISA) was performed to identify characteristic zooplankton groups associated with specific ecosites of Ashtamudi Lake (Fig. 5). The analysis revealed strong habitat specificity of major zooplankton groups along the freshwater-estuarine gradient. Copepoda and Protozoa exhibited high indicator values for the marine-influenced Neendakara ecosite, reflecting their preference for saline, tidally influenced conditions. Rotifera showed the highest indicator value for the freshwater-dominated Cherikkadavu ecosite, confirming their strong association with eutrophic, low-salinity environments. The semi-isolated brackish ecosite Puthenthuruth and the transitional ecosite Kidapram were characterized by moderate indicator values of multiple zooplankton groups, indicating mixed community composition driven by fluctuating salinity and nutrient inputs. Asramam ecosite exhibited intermediate indicator values for rotifers and protozoans, consistent with nutrient enrichment from urban runoff. The analysis highlights distinct ecosite-specific indicator assemblages and reinforces the utility of zooplankton as sensitive biological indicators of hydrological and water quality gradients in tropical estuarine wetlands.

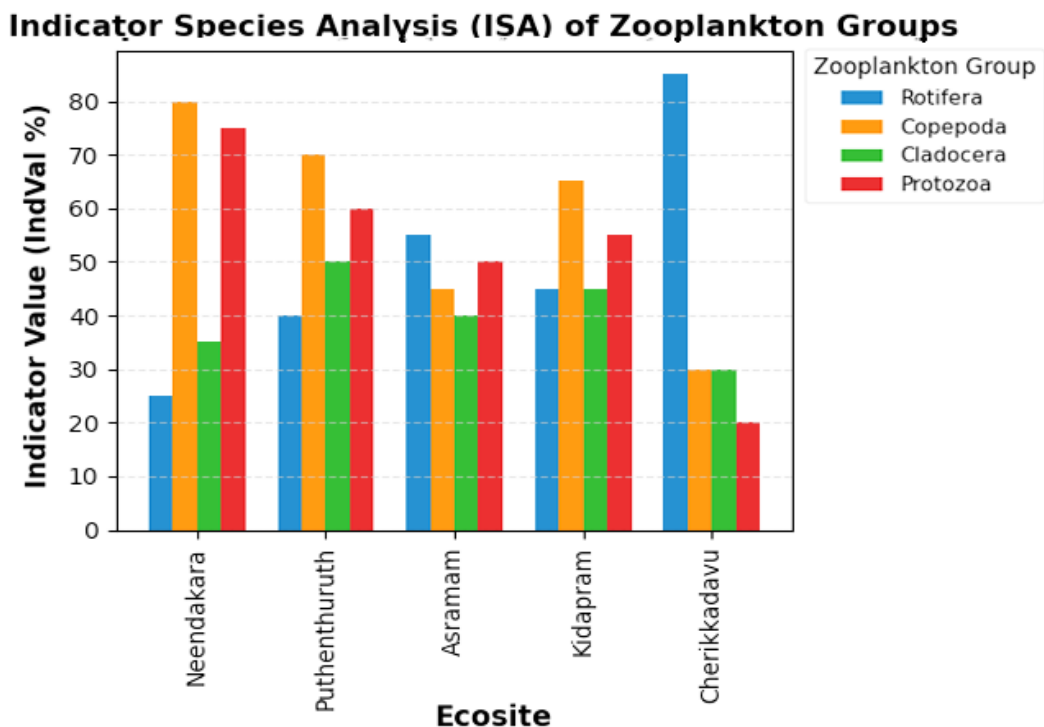


Figure 5. Indicator Species Analysis (ISA) of Zooplankton Groups Across Ecosites

4. DISCUSSIONS

The present investigation clearly demonstrates that seasonal hydrology and ecosite-specific environmental gradients jointly regulate water quality and zooplankton community dynamics

in Ashtamudi Lake. Seasonal variation in physicochemical parameters across the five ecosites, driven primarily by monsoonal freshwater inflow, tidal exchange, and anthropogenic inputs, resulted in marked spatial heterogeneity, which was statistically validated through Two-way ANOVA. The significant effects of season, ecosite, and their interaction on zooplankton abundance underscore the dynamic nature of tropical estuarine wetlands, where biological communities rapidly respond to changing environmental conditions (Nair et al., 1984; Jeppesen et al., 2005; Choi et al., 2023). Urban-influenced and semi-enclosed ecosites exhibited signs of nutrient enrichment, reduced dissolved oxygen, and elevated carbon dioxide, reflecting the impacts of organic loading and eutrophication, consistent with observations from other human-impacted wetlands (Smith et al., 1999; Walsh et al., 2005; World Water Assessment Programme, 2009). Correlation analysis further highlighted salinity, dissolved oxygen, nitrate, and phosphate as key drivers governing seasonal variability in water quality and biological productivity, reinforcing the role of nutrient dynamics and hydrological mixing in shaping wetland ecosystem functioning (Mitsch & Gosselink, 2000; Sharma, 2001).

Community-level multivariate analyses provided deeper ecological insight into zooplankton with environment relationships. NMDS ordination based on Bray-Curtis dissimilarity revealed clear spatial segregation of zooplankton assemblages along freshwater–brackish–marine gradients, with distinct clustering of freshwater, estuarine, and transitional ecosites and greater dispersion during the monsoon, reflecting enhanced habitat heterogeneity and nutrient influx (Clarke, 1993). CCA biplot analysis further elucidated species and environment linkages, demonstrating strong associations of rotifer-dominated assemblages with nutrient-enriched, low-salinity conditions and copepod, and protozoan-dominated communities with higher salinity and oxygen availability, in agreement with established estuarine ecological patterns (Verity & Smetacek, 1996; ter Braak, 1986). The Indicator Species Analysis strengthened these findings by identifying ecosite-specific indicator groups, confirming the diagnostic value of zooplankton as sensitive bioindicators of water quality gradients and anthropogenic stress (Dufrêne & Legendre, 1997; Chandel et al., 2023; Soumya & Biju, 2023). Collectively, the convergence of univariate and multivariate statistical evidence highlights that zooplankton community structure in Ashtamudi Lake is a direct reflection of seasonal hydrological forcing, nutrient enrichment, and localized human pressures, emphasizing the importance of integrated statistical approaches for ecological assessment and sustainable management of tropical Ramsar wetlands (Ramsar Secretariat, 2014; Arman et al., 2021; Singh et al., 2024).

5. CONCLUSIONS

The present study provides a comprehensive assessment of the seasonal dynamics of zooplankton communities and their ecological responses to water quality across five distinct ecosites of the Ramsar-designated Ashtamudi Lake. Integrated biological and physicochemical analyses revealed pronounced spatial and temporal variability in zooplankton abundance, diversity, and community structure, with monsoon season emerging as the most productive phase due to enhanced freshwater inflow, nutrient enrichment, and hydrological mixing. Rotifer dominance in freshwater and eutrophic ecosites such as Cherikkadavu and Asramam, copepod and protozoan prevalence in saline estuarine zones like Neendakara, and the high biological turnover observed in the transitional ecosite Kidapram collectively highlight the strong influence of salinity, dissolved oxygen, nitrate, and phosphate in structuring zooplankton assemblages. The application of robust statistical tools, including Two-way ANOVA, correlation analysis, NMDS, CCA, and Indicator Species Analysis, provided convergent evidence that both seasonal hydrology and ecosite-specific water quality jointly regulate zooplankton distribution and succession patterns. These findings confirm the effectiveness of zooplankton as sensitive bioindicators of ecosystem health and underscore the ecological significance of Ashtamudi Lake as a dynamic tropical estuarine system. The study establishes a valuable baseline dataset and analytical framework for long-term monitoring, impact assessment, and sustainable management of tropical wetlands facing increasing anthropogenic and climatic pressures.

Details of the AI usage are given below:

1. Grammarly AI used for Spelling and grammar corrections.
2. SciSpace AI used for reference finding and corrections.

Competing Interests

Author has declared that no competing interests exist.

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