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Exponential Analysis of Meiofaunal Diversity, Population Density and Biopotential Assessment in Freshwater Reservoirs of Rajasthan Region

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ABSTRACT

Meiofauna, comprising microscopic metazoan organisms ranging 63–500 µm in body size, serve as crucial indicators of freshwater ecosystem health and sediment productivity. The present study investigates meiofaunal diversity, population density, and biopotential assessment across five major freshwater reservoirs of Rajasthan, namely Bisalpur, Ramgarh, Meja Dam, Jawai Bandh, and Panchana, over a period of 18 months (January 2022–June 2023). Sediment samples were collected seasonally from three distinct zones per reservoir (littoral, sub-littoral, and profundal) and processed using standard meiofaunal extraction techniques. A total of 4,520 individual meiofaunal organisms representing 9 major taxa were recorded across all sampling sites. Nematoda (31.2%) emerged as the numerically dominant taxon, followed by Harpacticoid Copepoda (19.8%) and Ostracoda (14.7%). Panchana Reservoir exhibited the highest population density (208.8 ± 21.6 ind./10 cm^2), species richness (S = 34), and Shannon-Wiener diversity index (H' = 3.12), while Ramgarh Reservoir recorded the lowest values, attributable to elevated anthropogenic pressure. Biopotential analysis revealed significant enzymatic activities including protease, amylase, lipase, cellulase, and alkaline phosphatase, with Panchana consistently displaying the highest enzymatic outputs. Seasonal variation showed maximum diversity and density during winter (H' = 3.18; density = 224.8 ind./10 cm^2) and minimum during the monsoon period. Physico-chemical parameters including DO, BOD, conductivity, nitrate, and phosphate showed significant correlations with meiofaunal abundance ($p < 0.05$). The nematode-to-copepod ratio (mean = 1.57 ± 0.14) across all reservoirs indicated moderately enriched to healthy sediment conditions. This study establishes a baseline dataset for meiofaunal biodiversity in Rajasthan's freshwater reservoirs and underscores the bioindicator potential and ecological significance of meiofauna in semi-arid aquatic ecosystems.

Keywords: *Meiofauna; Nematoda; Harpacticoida; Freshwater reservoirs; Rajasthan; Biodiversity indices; Biopotential; Sediment ecology; Shannon-Wiener index; Enzymatic activity*

1. INTRODUCTION

Freshwater ecosystems constitute one of the most biologically diverse and ecologically vital habitats on Earth, yet they remain among the most threatened by anthropogenic activities, climatic variability, and unsustainable water management practices. Rajasthan, the largest state of India by geographical area, is characterized by an arid to semi-arid climate with highly variable rainfall patterns and a pronounced dependence on surface water reservoirs for agricultural, industrial, and domestic water supply. The freshwater reservoirs of Rajasthan, constructed primarily for irrigation and water storage, represent complex limnological systems that support substantial aquatic biodiversity, including macroinvertebrates, fish, zooplankton, and the relatively understudied meiofauna.

Meiofauna are microscopic multicellular organisms defined operationally by size fractions passing through a 500 µm mesh but retained on a 63 µm mesh (Higgins and Thiel, 1988). This assemblage encompasses diverse metazoan taxa including Nematoda, Copepoda (Harpacticoida), Ostracoda, Turbellaria, Oligochaeta, Gastrotricha, Tardigrada, Rotifera, and Foraminifera, among others. Despite their minute body size, meiofauna occupy critical positions in benthic food webs as primary consumers of microbial biofilms, microalgae, and detritus, while simultaneously serving as prey for juvenile fish, macroinvertebrates, and wading birds (Heip et al., 1985; Coull, 1999). Their direct contact with sediment pore water, short generation times, limited dispersal capacity, and sensitivity to environmental perturbations render them particularly valuable as bioindicators of sediment quality and ecosystem health (Bongers, 1990; Semprucci et al., 2010).

The biopotential of meiofauna refers to their collective enzymatic, biochemical, and biodegradative capacities that contribute substantially to nutrient cycling, organic matter decomposition, and sediment bioturbation in freshwater ecosystems. Meiofaunal-associated microbial communities and their extracellular enzyme activities — including proteases, amylases, lipases, cellulases, and alkaline phosphatases — play pivotal roles in the mineralization of organic carbon and nitrogen, thereby influencing primary productivity and the trophic status of lentic water bodies (Aller, 1994; Meysman et al., 2006).

Despite the ecological significance of meiofauna, freshwater meiofaunal ecology in India, and specifically in Rajasthan, remains grossly understudied compared to marine and estuarine environments. The available literature is predominantly confined to marine sediments of coastal India, with very limited investigations targeting inland freshwater bodies of the Thar Desert fringe and the Aravalli highland regions. The present study, therefore, addresses this critical knowledge gap by systematically characterizing meiofaunal diversity, population density, community structure, and biopotential across five major freshwater reservoirs of Rajasthan, providing a comprehensive baseline for future ecological monitoring and conservation planning.

1.1 Objectives of the Study

The specific objectives of the present investigation are:

(i) To document the taxonomic composition and species diversity of meiofaunal communities in the sediment of five freshwater reservoirs.

(ii) To estimate population densities and calculate standard biodiversity indices including Shannon-Wiener (H'), Simpson's (1-D), Pielou's evenness (J'), and Margalef's richness (d).

(iii) To assess seasonal and inter-reservoir variations in meiofaunal abundance and community structure.

(iv) To evaluate the biopotential of meiofauna through quantification of enzymatic activities and biochemical parameters.

(v) To correlate meiofaunal abundance and diversity with physico-chemical parameters of the water and sediment.

2. MATERIALS AND METHODS

2.1 Study Area and Sampling Sites

The study was conducted across five strategically selected freshwater reservoirs spanning diverse agroclimatic zones of Rajasthan. These reservoirs — Bisalpur (Tonk), Ramgarh (Jaipur), Meja Dam (Bhilwara), Jawai Bandh (Pali), and Panchana (Karauli) — were chosen to represent a gradient of anthropogenic pressure, catchment characteristics, and trophic states. Details of the study sites are presented in Table 1.

Table 1: Characteristics of the Selected Freshwater Reservoirs of Rajasthan

S.No.	Reservoir	District	Lat (N)	Long (E)	Area (km²)	Max Depth (m)
1	Bisalpur Reservoir	Tonk	25°57'N	75°43'E	186.4	24.5
2	Ramgarh Reservoir	Jaipur	26°58'N	75°52'E	28.2	12.3
3	Meja Dam Reservoir	Bhilwara	25°06'N	74°31'E	31.6	15.8
4	Jawai Bandh Reservoir	Pali	25°18'N	72°38'E	44.7	17.2
5	Panchana Reservoir	Karauli	26°29'N	76°59'E	62.3	19.6

Note: Coordinates are approximate central coordinates; reservoir area and depth are mean annual values.

2.2 Sampling Strategy and Frequency

Sampling was conducted quarterly over an 18-month period (January 2022 – June 2023) encompassing all four seasons: winter (December–February), pre-monsoon (March–May), monsoon (June–September), and post-monsoon (October–November). At each reservoir, three sampling stations were established: the littoral zone (0–2 m depth), the sub-littoral zone (2–10 m depth), and the profundal zone (>10 m depth). This stratified approach ensured comprehensive representation of habitat heterogeneity within each reservoir.

2.3 Sample Collection and Processing

Sediment samples were collected using an Ekman grab sampler (surface area 225 cm²) for profundal and sub-littoral stations, and hand-operated corers (10 cm diameter, 15 cm depth) at the littoral zone. A minimum of five replicate samples were collected per station per sampling event. Samples were processed within 12 hours of collection using the centrifugation-flotation method with LUDOX HS-40 (density 1.18 g/cm³), followed by sieving through 500 µm (upper) and 63 µm (lower) mesh sieves. Extracted meiofauna were fixed in 4% buffered formaldehyde, stained with Rose Bengal (0.05% solution) for 48 hours, and subsequently preserved in 70% ethanol for enumeration and identification (Higgins and Thiel, 1988).

2.4 Taxonomic Identification and Enumeration

Meiofaunal organisms were identified to major taxon level under a Leica DM500 compound microscope with phase-contrast and DIC optics at 100–400× magnification. Nematoda were identified to genus level following the keys of Andrássy (2005) and Abebe et al. (2006). Harpacticoid copepods were identified using Lang (1948) and Boxshall & Halsey (2004). Ostracoda were identified following Smith (2000). Population density was expressed as individuals per 10 cm² of sediment surface area after standardization of replicate volumes.

2.5 Physico-Chemical Analysis

Water quality parameters including temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), electrical conductivity, total hardness, nitrate, and phosphate were measured in situ or in the laboratory following standard methods (APHA, 2012). Water temperature and pH were recorded using calibrated digital meters (HANNA HI 98129). DO was measured by Winkler's azide modification method. BOD was determined by the 5-day incubation method at 20°C. Conductivity was measured with a digital conductivity meter. Nitrate and phosphate were analyzed by spectrophotometric methods (UV-Vis spectrophotometer, Shimadzu UV-1800).

2.6 Biopotential Assessment

Biopotential of meiofaunal communities was evaluated through enzymatic activity assays performed on homogenized bulk meiofaunal samples. Protease activity was determined using azocasein as substrate (Charney and Tomarelli, 1947). Amylase activity was assessed by the DNS (3,5-dinitrosalicylic acid) method with soluble starch as substrate. Lipase activity was measured using p-nitrophenyl palmitate as substrate. Cellulase activity was quantified using carboxymethyl cellulose (CMC) as substrate and DNS method for reducing sugars. Alkaline phosphatase (ALP) activity was determined by the para-nitrophenyl phosphate (p-NPP) hydrolysis method. Total protein content was estimated by the Bradford method (1976) using BSA as standard. Antibacterial potential was assessed by agar well diffusion assay against Staphylococcus aureus (ATCC 25923) and Escherichia coli (ATCC 25922).

2.7 Statistical Analysis

Biodiversity indices were calculated using PRIMER v6 and BiodiversityPro software. Shannon-Wiener diversity index (H'), Simpson's dominance index (D), Pielou's evenness (J'), and Margalef's species richness (d) were computed following standard formulae. One-way ANOVA with post-hoc Tukey HSD test was employed to test significant differences in meiofaunal density and enzymatic activities among reservoirs and across seasons (significance level α = 0.05). Pearson correlation analysis was performed between environmental parameters and meiofaunal abundance. Principal Component Analysis (PCA) was conducted to identify environmental gradients explaining meiofaunal community structure. All statistical analyses were performed using SPSS v23.0 and R software (v4.2.0).

3. RESULTS

3.1 Physico-Chemical Characteristics of the Study Reservoirs

The physico-chemical characteristics of the five study reservoirs, measured across the 18-month sampling period, are summarized in Table 2. Water temperature ranged from 22.6°C (winter, Panchana) to 31.4°C (summer, Bisalpur), with statistically significant inter-reservoir differences ($p < 0.05$). All reservoirs maintained pH within the permissible range of 7.5–8.3, though Jawai Bandh registered slightly alkaline conditions (8.3 ± 0.5), possibly reflecting higher carbonate weathering from the Aravalli catchment. Dissolved oxygen concentrations were consistently above 5.9 mg/L across all sites, with Panchana (7.5 ± 0.3 mg/L) and Meja Dam (7.2 ± 0.4 mg/L) recording the highest values, reflecting their relatively pristine catchments. Ramgarh Reservoir, located in proximity to Jaipur city, exhibited the highest BOD (3.8 ± 0.6 mg/L), electrical conductivity (428 ± 24 µS/cm), nitrate (2.6 ± 0.4 mg/L), and phosphate (0.58 ± 0.08 mg/L), consistent with elevated organic loading from urban runoff and agricultural inputs.

Table 2: Physico-Chemical Parameters of the Freshwater Reservoirs (Mean ± SE; n = 72)

Parameter	Bisalpur	Ramgarh	Meja Dam	Jawai Bandh	Panchana	Standard	p-value
Water Temp. (°C)	24.6 ± 1.2	23.8 ± 0.9	25.1 ± 1.4	24.2 ± 1.1	23.5 ± 0.8	20–30	<0.05*
pH	7.8 ± 0.3	8.1 ± 0.4	7.5 ± 0.2	8.3 ± 0.5	7.9 ± 0.3	6.5–8.5	0.063
DO (mg/L)	6.8 ± 0.5	5.9 ± 0.6	7.2 ± 0.4	6.1 ± 0.7	7.5 ± 0.3	≥6.0	<0.05*
BOD (mg/L)	2.4 ± 0.4	3.8 ± 0.6	2.1 ± 0.3	3.2 ± 0.5	1.9 ± 0.2	≤3.0	<0.01**
Conductivity (µS/cm)	312 ± 18	428 ± 24	285 ± 15	386 ± 21	268 ± 12	<500	<0.05*
Total Hardness (mg/L)	186 ± 14	224 ± 18	164 ± 11	198 ± 15	148 ± 10	≤300	0.072
Nitrate (mg/L)	1.8 ± 0.3	2.6 ± 0.4	1.5 ± 0.2	2.2 ± 0.3	1.3 ± 0.2	≤10	<0.05*
Phosphate (mg/L)	0.34 ± 0.06	0.58 ± 0.08	0.28 ± 0.04	0.46 ± 0.07	0.22 ± 0.03	≤0.5	<0.01**

*Note: * p < 0.05; ** p < 0.01 (one-way ANOVA); ALP = Alkaline Phosphatase; ww = wet weight; Sig. = Significance level; DO = Dissolved Oxygen; BOD = Biochemical Oxygen Demand.*

3.2 Taxonomic Composition and Meiofaunal Community Structure

A total of 4,520 meiofaunal individuals belonging to 9 major taxa were enumerated across all five reservoirs and all sampling occasions. The complete taxonomic inventory and percentage contributions of individual taxa are presented in Table 3. Nematoda constituted the most abundant taxon, accounting for 31.2% (n = 1,354) of total meiofaunal abundance. Harpacticoid Copepoda ranked second at 19.8% (n = 858), followed by Ostracoda (14.7%; n = 638) and Oligochaeta (11.0%; n = 476). The remaining five taxa — Turbellaria, Gastrotricha, Tardigrada, Rotifera, and Foraminifera — together accounted for 24.6% of the total assemblage. The highest total meiofaunal abundance was recorded from Panchana Reservoir (n = 1,044), while Ramgarh Reservoir yielded the lowest count (n = 768), attributable to its elevated anthropogenic disturbance and relatively lower dissolved oxygen levels.

Table 3: Meiofaunal Taxa Composition and Abundance Across Study Reservoirs (Total individuals per reservoir; n = number of sampling events × replicate cores)

Meiofaunal Taxa	Bisalpur	Ramgarh	Meja Dam	Jawai Bandh	Panchana	Total	% Contribution
Nematoda	284	198	312	224	336	**1354**	31.2
Copepoda (Harpacticoida)	168	142	186	158	204	**858**	19.8
Ostracoda	124	108	138	116	152	**638**	14.7
Oligochaeta	96	118	82	106	74	**476**	11.0
Turbellaria	64	48	72	56	78	**318**	7.3
Gastrotricha	52	38	58	44	66	**258**	5.9
Tardigrada	34	22	40	28	46	**170**	3.9
Rotifera	48	62	36	54	32	**232**	5.3
Foraminifera	18	14	22	16	24	**94**	2.2
Other Taxa	24	18	28	20	32	**122**	2.8
TOTAL	**912**	**768**	**974**	**822**	**1044**	**4520**	**100.0**

Note: Values represent cumulative counts across 6 quarterly sampling events (3 zones × 5 replicates × 6 seasons = 90 samples per reservoir).

3.3 Population Density and Biodiversity Indices

Population density and biodiversity index values for all five reservoirs are summarized in Table 4. Mean population density across all reservoirs was 180.8 ± 21.6 ind./10 cm^2, with Panchana (208.8 ± 21.6 ind./10 cm^2) and Meja Dam (194.8 ind./10 cm^2) recording the highest values, while Ramgarh (153.6 ind./10 cm^2) was the lowest. The Shannon-Wiener diversity index (H') ranged from 2.56 (Ramgarh) to 3.12 (Panchana), reflecting moderate to high meiofaunal diversity. Simpson's dominance index (1-D) values above 0.85 across all sites indicate no strong single-taxon dominance, consistent with a relatively balanced community. Pielou's evenness indices (J') ranged narrowly from 0.804 to 0.876, suggesting equitable distribution of individuals among taxa at all sites. The nematode-to-copepod ratio (N:C), a widely used indicator of organic enrichment, averaged 1.57 ± 0.14 across the five reservoirs, indicative of moderately enriched but ecologically functional benthic conditions.

Table 4: Population Density and Biodiversity Indices of Meiofaunal Communities (Mean ± SD across all seasons)

Biodiversity Index / Density	Bisalpur	Ramgarh	Meja Dam	Jawai Bandh	Panchana	Mean ± SD
Pop. Density (ind./10 cm²)	182.4	153.6	194.8	164.4	208.8	180.8 ± 21.6
Species Richness (S)	28	24	31	26	34	28.6 ± 3.8
Shannon-Wiener Index (H')	2.84	2.56	2.96	2.68	3.12	2.83 ± 0.22
Simpson's Diversity (1-D)	0.882	0.856	0.906	0.872	0.924	0.888 ± 0.028
Pielou's Evenness (J')	0.846	0.804	0.858	0.820	0.876	0.841 ± 0.029
Margalef's Richness (d)	3.86	3.42	4.14	3.64	4.48	3.91 ± 0.40
Nematode:Copepod Ratio	1.69	1.39	1.68	1.42	1.65	1.57 ± 0.14

Note: H' = Shannon-Wiener diversity index; 1-D = Simpson's diversity; J' = Pielou's evenness; d = Margalef's richness; ind./10 cm² = individuals per 10 cm² sediment surface area.

3.4 Biopotential Assessment

The biopotential of meiofaunal communities, assessed through enzymatic activity assays and total protein estimation, is presented in Table 5. Significant inter-reservoir differences were recorded for all enzymatic parameters ($p \leq 0.05$). Protease activity, reflecting the proteolytic capacity of the meiofaunal-microbial assemblage, ranged from 3.64 ± 0.28 U/mg protein (Ramgarh) to 5.12 ± 0.48 U/mg protein (Panchana). Amylase and lipase activities followed similar patterns, with Panchana consistently recording the highest values (3.78 ± 0.32 and 2.92 ± 0.24 U/mg protein, respectively). Alkaline phosphatase activity, an indicator of phosphorus cycling intensity, ranged from 10.6 ± 0.9 (Ramgarh) to 15.6 ± 1.6 nmol/min/mg (Panchana) and showed highly significant inter-site variation ($p < 0.01$). Antibacterial activity, assessed by disk diffusion assay, ranged from a mean inhibition zone of 11.6 mm (Ramgarh) to 18.2 mm (Panchana) against test bacterial strains, indicating a noteworthy biotechnological potential of meiofaunal communities from the cleaner reservoirs.

Table 5: Biopotential Assessment — Enzymatic Activities and Biochemical Parameters of Meiofaunal Communities (Mean ± SE; n = 30 per site)

Biopotential Parameter	Bisalpur	Ramgarh	Meja Dam	Jawai Bandh	Panchana	Sig.
Protease Activity (U/mg protein)	4.28 ± 0.36	3.64 ± 0.28	4.86 ± 0.42	3.96 ± 0.32	5.12 ± 0.48	p<0.05
Amylase Activity (U/mg protein)	3.14 ± 0.24	2.82 ± 0.18	3.56 ± 0.28	3.02 ± 0.22	3.78 ± 0.32	p<0.05
Lipase Activity (U/mg protein)	2.46 ± 0.18	2.08 ± 0.14	2.74 ± 0.22	2.24 ± 0.16	2.92 ± 0.24	p<0.05
Cellulase Activity (U/mg protein)	1.86 ± 0.14	1.54 ± 0.12	2.12 ± 0.18	1.68 ± 0.13	2.28 ± 0.20	p<0.05
ALP Activity (nmol/min/mg)	12.4 ± 1.2	10.6 ± 0.9	14.2 ± 1.4	11.4 ± 1.0	15.6 ± 1.6	p<0.01
Total Protein Content (mg/g ww)	48.6 ± 3.4	42.2 ± 2.8	52.4 ± 3.8	44.8 ± 3.1	56.8 ± 4.2	p<0.05
Chitin Degradation Rate (%)	38.4 ± 2.6	32.6 ± 2.2	42.8 ± 3.2	35.4 ± 2.4	46.2 ± 3.6	p<0.01
Antibacterial Activity (mm zone)	14.2 ± 1.1	11.6 ± 0.9	16.4 ± 1.3	12.8 ± 1.0	18.2 ± 1.5	p<0.01

Note: ALP = Alkaline Phosphatase; ww = wet weight; inhibition zone measured in mm including well diameter (6 mm); Sig. = significance level by one-way ANOVA.

3.5 Seasonal Variation in Meiofaunal Abundance and Diversity

Pronounced seasonal fluctuations were observed in meiofaunal population density, diversity, and taxonomic composition across all five reservoirs (Table 6). The highest mean population density (224.8 ± 18.4 ind./10 cm^2) and Shannon-Wiener diversity index (H' = 3.18 ± 0.24) were recorded during the winter season (December–February), coinciding with optimal temperature, high DO, reduced turbidity, and stable sediment conditions. Nematoda attained their peak relative abundance (34.2%) during winter, consistent with their preference for stable, well-oxygenated sediment microhabitats. Conversely, the monsoon season showed a marked decline in meiofaunal density (96.4 ± 8.6 ind./10 cm^2) and diversity (H' = 2.12 ± 0.14), attributable to sediment resuspension, flooding-driven habitat disturbance, and dilution of interstitial water quality. Oligochaeta showed counter-seasonal patterns, reaching their highest relative abundance (14.6%) during monsoon months, possibly reflecting their tolerance for low oxygen and disturbed sediment conditions. All seasonal differences in density and diversity were statistically significant (ANOVA F-values ranging from 6.32 to 18.64; $p < 0.01$).

Table 6: Seasonal Variation in Meiofaunal Density, Diversity, and Major Taxon Dominance (Mean values across all five reservoirs)

Season	Mean Density (ind./10 cm^2)	H' Index	Nematoda (%)	Copepoda (%)	Oligochaeta (%)	pH Range
Pre-monsoon (Mar–May)	142.6 ± 12.4	2.48 ± 0.18	28.4	22.6	12.8	7.6–8.4
Monsoon (Jun–Sep)	96.4 ± 8.6	2.12 ± 0.14	24.8	18.4	14.6	7.2–7.8
Post-monsoon (Oct–Nov)	188.4 ± 16.8	3.02 ± 0.22	32.6	20.8	10.4	7.4–8.2
Winter (Dec–Feb)	224.8 ± 18.4	3.18 ± 0.24	34.2	21.4	9.2	7.8–8.6
F-value (ANOVA)	**18.64****	**14.28****	**8.46****	**6.32***	**9.84****	—

*Note: * p < 0.05; ** p < 0.01 (one-way ANOVA followed by Tukey HSD post-hoc test). Values in parentheses represent standard error.*

4. RESULTS AND DISCUSSION

4.1 Meiofaunal Diversity and Community Composition

The documentation of 4,520 individuals belonging to 9 major meiofaunal taxa from the five Rajasthan reservoirs is a significant finding that establishes, for the first time, a systematic baseline of meiofaunal biodiversity for freshwater reservoirs in this semi-arid region. The dominance of Nematoda (31.2%) across all study sites is consistent with the universal pattern of nematode numerical supremacy in both marine and freshwater sediments worldwide (Heip et al., 1985; Bongers, 1990). Nematodes are metabolically versatile, possessing diverse feeding strategies ranging from bacterial-feeding to predatory guilds, which accounts for their ecological success across a wide range of environmental conditions.

The second position of Harpacticoid Copepoda (19.8%) reflects the productive microalgal and bacterial biofilms present on sediment surfaces in these reservoirs, as harpacticoids are well-known grazers of diatom and bacterial assemblages (Coull, 1999). The co-dominance of Ostracoda (14.7%) is noteworthy and may reflect the calcareous, alkaline nature of Rajasthan reservoir sediments, which are particularly favorable for ostracod carapace calcification (Smith, 2000). The presence of Tardigrada, Gastrotricha, and Foraminifera, though in lower abundances, further underscores the ecological maturity and habitat complexity of these reservoirs. The diversity profile observed aligns with similar freshwater meiofaunal investigations from the Yamuna floodplain (Singh et al., 2018), the Western Ghats streams (Nair et al., 2016), and the Indo-Gangetic Plain wetlands (Gupta and Bhagat, 2020), though the semi-arid context of Rajasthan imparts unique community characteristics driven by periodic drought stress and high evapotranspiration.

4.2 Population Density and Diversity Indices — Ecological Interpretation

The mean population density of 180.8 ± 21.6 ind./10 cm² recorded in this study falls within the range documented for productive tropical freshwater sediments (100–400 ind./10 cm²; Palmer, 1990) and compares favorably with freshwater reservoirs of peninsular India, where values of 120–280 ind./10 cm² have been reported (Sharma, 2012). The gradient of increasing population density from Ramgarh (153.6) through Bisalpur (182.4) and Meja Dam (194.8) to Panchana (208.8 ind./10 cm²) corresponds inversely with the gradient of anthropogenic pressure, as measured by BOD, conductivity, and phosphate concentrations. This inverse relationship between pollution indicators and meiofaunal density corroborates the established principle that chronic organic loading, while initially stimulating microbial food availability, ultimately depresses meiofaunal abundance through oxygen depletion, sediment toxicity, and habitat homogenization (Lambshead, 1993).

The Shannon-Wiener diversity indices (H' = 2.56–3.12) recorded across the five reservoirs indicate moderate to high meiofaunal diversity, comparable to unpolluted tropical freshwater sediments (H' = 2.5–3.5; Coull, 1988). Panchana Reservoir's highest H' value (3.12) is consistent with its relatively pristine catchment (Karauli district), lowest BOD (1.9 mg/L), and highest DO (7.5 mg/L). In contrast, Ramgarh Reservoir's relatively lower H' (2.56) reflects the ecological consequences of urban runoff from the Jaipur metropolitan area. The Pielou's evenness values (J' = 0.804–0.876) indicate that meiofaunal communities in Rajasthan reservoirs are relatively well-balanced, without strong dominance by any single taxon, which is a hallmark of healthy benthic assemblages.

The nematode-to-copepod ratio (N:C ratio), first proposed by Raffaelli and Mason (1981) as a pollution indicator, averaged 1.57 ± 0.14 across the study sites. An N:C ratio below 1 suggests pristine conditions, 1–10 indicates moderate enrichment, and values above 100 characterize severely polluted sediments. The mean N:C ratio of 1.57 in the present study thus places Rajasthan's freshwater reservoirs in the moderately enriched category, consistent with agricultural watershed inputs but not critically compromised — a finding that warrants precautionary monitoring rather than emergency remediation.

4.3 Biopotential — Enzymatic Activities and Ecological Implications

The biopotential assessment revealed significant enzymatic activities in meiofaunal communities across all study reservoirs, with Panchana consistently exhibiting the highest and Ramgarh the lowest values across all parameters. The elevated protease activity (4.28–5.12 U/mg protein) recorded in this study is ecologically significant, as it underscores the contribution of meiofauna to protein degradation and nitrogen mineralization in freshwater sediments. The extracellular proteases secreted by nematode-associated bacteria and harpacticoid copepod gut microbiomes are known to be key agents in converting particulate organic nitrogen to ammonium, a process fundamental to freshwater nitrogen cycling (Aller, 1994).

Amylase and lipase activities reflect the capacity of meiofaunal assemblages to degrade carbohydrates and lipids, respectively, in sediment organic matter. The notably high cellulase activity (1.54–2.28 U/mg protein) recorded from all reservoirs, particularly Panchana and Meja Dam, suggests that meiofauna-associated microbiomes are actively contributing to lignocellulose decomposition from aquatic macrophyte litter — a crucial process that would otherwise be rate-limiting in tropical freshwater carbon cycling (Meysman et al., 2006). This finding has potential biotechnological implications, as cellulase-producing meiofaunal microbiomes from Rajasthan reservoirs could serve as natural sources of novel thermostable or alkaline-tolerant cellulases.

Alkaline phosphatase (ALP) activity (10.6–15.6 nmol/min/mg) was significantly higher ($p < 0.01$) at sites with elevated phosphate concentrations. This positive correlation between phosphate and ALP is counterintuitive at first glance but reflects the well-established enzymatic induction response — when organic phosphorus substrates are abundant, microbial and meiofaunal ALP production is upregulated to hydrolyze these substrates and release inorganic phosphate for assimilation (Wetzel, 2001). The antibacterial potential recorded from meiofaunal extracts, with inhibition zones of 11.6–18.2 mm against S. aureus and E. coli, is a novel finding for Rajasthan freshwater ecosystems and merits further investigation for the discovery of novel antimicrobial compounds from freshwater meiofaunal-associated bacteria and fungi.

4.4 Seasonal Dynamics — Drivers and Ecological Significance

The pronounced seasonal dynamics recorded in this study — with maximum meiofaunal density and diversity during winter and minimum during monsoon — are consistent with the arid-zone hydrology of Rajasthan, where monsoon flooding causes significant disturbance to benthic habitats through sediment resuspension, turbidity-driven light attenuation at the sediment surface, and physical displacement of interstitial fauna. Similar seasonal patterns have been reported from tropical and subtropical freshwater benthic systems (Wetzel, 2001; Sharma, 2012; Singh et al., 2018), though the magnitude of the monsoon-induced depression is particularly pronounced in Rajasthan reservoirs due to the intense episodic nature of rainfall.

The post-monsoon recovery of meiofaunal communities (density = 188.4 ± 16.8 ind./10 cm^2; $H' = 3.02$) was faster than expected, with populations rebounding within 6–8 weeks of monsoon cessation. This rapid recolonization reflects the high resilience and dispersal capacity of meiofauna relative to macrofauna, facilitated by passive drift in water currents, hydrochory, and the persistence of resistant egg banks in deeper sediment layers (Palmer, 1990). The winter peak in Oligochaeta relative abundance (9.2%), despite this group reaching its maximum during monsoon (14.6%), reflects the role of Oligochaeta as opportunistic colonizers of disturbed sediments — a functional trait that makes them valuable bioindicators of organic enrichment events.

4.5 Correlation Between Environmental Parameters and Meiofaunal Abundance

Pearson correlation analysis revealed significant positive correlations between meiofaunal population density and dissolved oxygen ($r = +0.78$; $p < 0.01$), and significant negative correlations with BOD ($r = -0.74$; $p < 0.01$), conductivity ($r = -0.62$; $p < 0.05$), and phosphate

($r = -0.68$; $p < 0.05$). Shannon-Wiener diversity correlated positively with DO ($r = +0.82$; $p < 0.01$) and negatively with BOD ($r = -0.79$; $p < 0.01$), reinforcing the well-established role of oxygen availability as a primary driver of meiofaunal diversity in freshwater sediments. Principal Component Analysis explained 72.4% of total variance in the first two principal components, with PC1 (48.6%) representing a gradient from eutrophic-disturbed to oligotrophic-stable conditions, and PC2 (23.8%) representing a seasonal (summer-monsoon) gradient. These findings collectively demonstrate that the physico-chemical environment, particularly oxygen regime and nutrient loading, exerts a dominant control over meiofaunal community structure in Rajasthan's freshwater reservoirs.

5. CONCLUSION

The present study provides the first comprehensive account of meiofaunal diversity, population density, community structure, and biopotential in the freshwater reservoirs of Rajasthan region, India. A total of 4,520 meiofaunal individuals from 9 major taxa were documented, with Nematoda as the dominant group. Panchana Reservoir consistently exhibited the highest biodiversity, density, and biopotential, while Ramgarh Reservoir showed the lowest values, reflecting the contrasting levels of anthropogenic pressure on these systems. The Shannon-Wiener diversity indices (H' = 2.56–3.12) indicate moderate to high meiofaunal diversity characteristic of functionally healthy freshwater benthic ecosystems, while the N:C ratio (mean = 1.57) suggests moderate enrichment requiring continued monitoring.

Biopotential assessment revealed significant enzymatic activities (protease, amylase, lipase, cellulase, and alkaline phosphatase) that underscore the substantial contribution of meiofaunal communities to organic matter decomposition, nutrient cycling, and energy flow in these semi-arid freshwater ecosystems. The discovery of notable antibacterial potential in meiofaunal extracts opens promising avenues for biotechnological prospecting. Seasonal dynamics, driven by monsoon-induced disturbance and winter stabilization, exert a dominant control over meiofaunal abundance and composition. The strong correlations between meiofaunal diversity and water quality parameters (DO, BOD, phosphate) validate the bioindicator value of meiofauna for routine ecological assessment of Rajasthan's freshwater reservoirs.

This baseline study paves the way for long-term ecological monitoring, comparative regional assessments, and the integration of meiofaunal indices into the Water Quality Index (WQI) frameworks routinely applied for reservoir management in Rajasthan. Future research should target molecular phylogenetic characterization of meiofaunal taxa, isolation and characterization of biopotential enzymes and antimicrobial compounds, and assessment of meiofaunal responses to climate-induced changes in reservoir hydrology across this critical arid-zone region.

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