

# Limnological Variability and Zooplankton Dynamics in High-altitude Lakes of Tawang District of Arunachal Pradesh, India

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## ABSTRACT

High-altitude lakes (HALs) represent unique ecosystems characterized by extreme climatic conditions, including low temperatures, high ultraviolet radiation, and oligotrophic waters. This study investigates limnological variability and zooplankton dynamics in five selected HALs in the Tawang district of Arunachal Pradesh over 2 years (December 2020 to December 2022). Seasonal samplings revealed substantial fluctuations in water quality parameters like pH, dissolved oxygen, conductivity, and temperature. A total of 20 zooplankton species, belonging to Rotifera, Cladocera, Copepoda, and Ostracoda, were documented, with Rotifera being the most dominant. Seasonal variations were evident, with monsoon supporting the highest zooplankton diversity and abundance, whereas winter conditions significantly reduced zooplankton populations. Canonical Correspondence Analysis (CCA) highlighted strong correlations between zooplankton distribution and environmental factors like dissolved oxygen, alkalinity, and temperature. These findings provide critical insights into the ecological status and seasonal dynamics of HALs, offering valuable information for their conservation and management amid increasing environmental and anthropogenic pressures.

**Key words:** Ecosystem, High-altitude lakes, Limnology, Seasonal variations, Zooplankton

## INTRODUCTION

High-altitude lakes (HALs), situated at elevations exceeding 3,000 m amsl, play a crucial role in the delicate ecosystems of the mountainous regions, serving as vital sources of freshwater habitats for unique flora and fauna, and indicators of environmental change (Neupane et al. 2010, Raut et al. 2013, Islam et al. 2021). HALs in remote and harsh environments represent unique ecosystems characterized by extreme climatic conditions such as low temperatures, high ultraviolet radiation, and oligotrophic water conditions (Tartari et al. 1998, Zutshi and Gopal 2000, Sommaruga 2001, Gopal et al. 2002, Gujja et al. 2003, Raut et al. 2013, Rashid et al. 2017, Cantonati et al. 2021, Maharjan et al. 2018). These lakes are often found in alpine regions where the interplay between abiotic factors and biotic communities shapes their limnological characteristics and ecological dynamics (Straskrbova et al. 1999). Despite their remote locations, these lakes are not immune to the impacts of human activities and climate change, facing threats such as acidification and eutrophication. Conservation and sustainable management of HALs

are of utmost importance, as they provide a wide range of ecological services from supporting diverse avian communities to regulating the hydrological balance of the surrounding regions (Kumar et al. 2006, Raut et al. 2013, Tiberti et al. 2019, Hofmann et al. 2021).

Limnological studies on HALs have revealed their vulnerability to environmental changes with fluctuations in water quality parameters and biotic communities often linked to seasonal variations in climatic factors (Winder et al. 2009, Sommaruga 2015, Råman Vinnå et al. 2021). In particular, zooplankton, which plays a crucial role in aquatic food webs, exhibit distinct seasonal patterns in their diversity, abundance, and community composition (Winder and Schindler 2004). Zooplankton are a diverse assemblage of tiny aquatic organisms that play a vital role in the delicate balance of ecosystems. However, their significance is often overshadowed by the flora and fauna that inhabit these environments (Obiuto et al. 2022). These microscopic organisms are the foundation of the food web, serving as the primary consumers of phytoplankton and providing sustenance for a wide array of significant aquatic life (Li et al. 2023). They mediate the link between

phytoplankton and fish, and play a dynamic role in the cycling of organic materials in aquatic ecosystems (Schriver et al. 1995, Lomartire et al. 2021). Many of these shallow freshwater ecosystems in the circumpolar Arctic region contain large stocks of benthic microbial mats that grow in relatively nutrient-rich conditions (McLaren 1964, Moore 1978, Kosobokova and Hirche 2009, Rautio et al. 2011, Schartau et al. 2022). The diversity and abundance of zooplankton play a major role in the aquaculture management as they are primary consumers of phytoplankton and recycle nutrients (Cunha et al. 2008, Panwar and Malik 2016, Fan et al. 2020, Ramlee et al. 2021). Understanding the seasonal dynamics of limnological parameters and zooplankton populations in HALs is important for assessing their ecological status, identifying potential threats, and developing effective conservation strategies (Vinebrooke and Leavitt 1999). The HALs of Tawang serve as critical habitats for several threatened avian species, including the critically endangered Baer's Pochard (*Aythya baeri*) and the vulnerable Black-necked Crane (*Grus nigricollis*), documented in these ecosystems (Mishra et al. 2004, Anonymous 2010), along with the vulnerable Ruddy Shelduck (*Tadorna ferruginea*) that breeds in these Himalayan wetlands (Jamwal 2020). The surrounding landscapes support endangered mammals such as snow leopards, musk deer, red pandas, takin, and both Chinese and red goral (Mazumdar et al. 2011), while also harboring a diverse array of flowering and ethnobotanically significant plant species, including various genera like *Aconitum*, *Rhododendron*, *Gentiana*, and culturally important Brahma Kamal (*Saussurea obvallata*) (Bharali and Khan 2011, Dutta et al. 2013). However, these ecosystems face multiple anthropogenic threats, and current scientific understanding remains limited due to accessibility challenges and harsh environmental conditions (Mazumdar et al. 2011, Kanwal et al. 2013, Dutta et al. 2013). Despite their ecological importance, the HALs of Tawang remained largely understudied, with limited information on their limnological characteristics and zooplankton communities. This study aims to bridge the knowledge gap by investigating seasonal variability in limnological parameters and zooplankton dynamics across five

HALs in Tawang district. By addressing these objectives, this study contributes to a better understanding of the ecological dynamics of HALs, providing a baseline for future monitoring efforts and informing conservation strategies to preserve these unique and vulnerable ecosystems.

## METHODOLOGY

### Study area

The study was conducted in five HALs (Kyalem, Nagula, Ptso, Sela, and Shungatser) in the Tawang district of Arunachal Pradesh (Fig. 1). The district shares international borders with Tibet and Bhutan and is characterised by mountainous topography, featuring snow-covered peaks and valleys. The region experiences significant precipitation ranging from 1474 to 1831 mm with an average annual rainfall of 1653 mm. Rainfall patterns show a peak in July (350 mm) and minima in January and December (3 mm), while temperature variations range from 8.2°C in January to 20.88°C in August. According to the National Wetland Atlas by ISRO (2009), the district hosts 204 HALs, the second-highest concentration in Arunachal Pradesh. The area is inhabited by the Monpa tribe, whose cultural identity is deeply intertwined with Tibetan traditions and Buddhist philosophy. They have a profound spiritual connection with the natural landscape and revere the lakes as sacred spiritual conduits. Traditionally, they organize pilgrimages and circumambulations around lakes during religious ceremonies. Their beliefs in these water bodies reflect a sacred intermediary between human and divine realms.

### Data collection

*Sampling and analysis of limnological parameters*  
Limnological variables of the selected HALs were sampled seasonally over two years (December 2020 to December 2022). Water samples have been collected in a 1 liter plastic bottle (acid-washed) for water analysis. Water quality parameters, like pH, dissolved oxygen (DO), conductivity, and total dissolved solids (TDS), were measured in the field using a Hanna portable multiparameter testing kit. Alkalinity, hardness, and free carbon dioxide (FCO<sub>2</sub>) were analysed according to standard methods

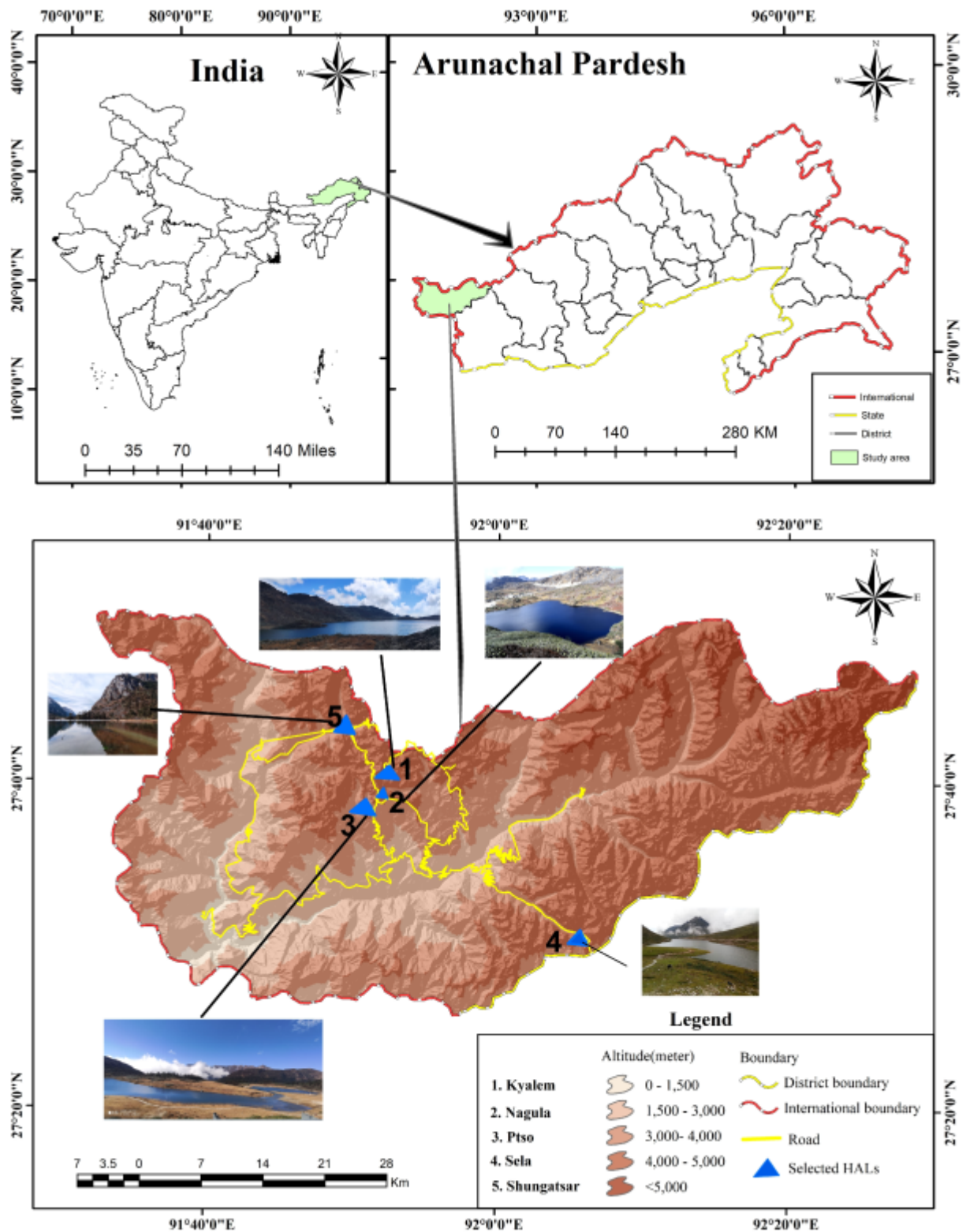


Figure 1. Location map of the study area

(Anonymous 2005, 2012).

*Sampling and analysis of zooplankton*

Zooplankton samples were systematically collected from diverse water depths - surface (0-3 m), littoral

region (5-10 m), and bottom mud (0-10 m) - using a specialized plankton net with bolting silk No. 20 (75-µm mesh) during early morning hours (8-10 am). In the field, samples were immediately stabilized using

a 4% Lugol solution to prevent cellular activity and enhance staining. Laboratory processing involved overnight dark sedimentation, siphoning 900 ml of the upper layer, and retaining a 100 ml homogenized sample. For the taxonomic identification, a 1ml sub-sample was meticulously examined under a Zeiss Primostar 3 Microscope at 100x magnification. Zooplankton genera were classified using comprehensive morphological analyses and cross-referencing multiple authoritative taxonomic resources to ensure precise and systematic ecological documentation (Ward and Whipple 1992, Korinek 2002, Anonymous 2005, Pathani and Upadhyay 2006, Munshi et al. 2010).

### Statistical analysis

Diversity indices such as the Shannon-Wiener index (1949), Berger-Parker's dominance index (1970), and Pielou's species evenness (1966) were calculated using the standard methods. To assess seasonal variability and similarity in limnological data, a Bray-Curtis cluster analysis was applied. Pearson's correlation was used to understand the correlation between the physico-chemical variables. Canonical Correspondence Analysis (CCA), a multivariate analysis technique, was used to explore the relationship between limnological parameters and zooplankton distribution in PAST 3. CCA (unimodal model) has been considered an adequate multivariate analysis for phytoplankton data (ter Braak et al. 2002).

## RESULTS

### Seasonal variation of limnological parameters

The seasonal variation of water parameters across the studied lakes revealed significant fluctuations. DO peaked at 7.37 mg/l in Nagula Lake during monsoon, followed by 6.61 mg/l in Shungatser Lake, and was lowest at 1.61 mg/l in Nagula Lake during post-monsoon. pH reached its highest at 8.5 in Sela Lake during pre-monsoon, followed by 8.23 in Kyalem Lake during monsoon, and dropped to its lowest at 7.49 in Ptso Lake during monsoon. FCO<sub>2</sub> reached its maximum at 1.24 mg/l in Nagula Lake during winter and 0.93 mg/l during pre-monsoon, and descended to 0.45 mg/l in Ptso Lake during monsoon. Alkalinity was highest in Sela Lake during

winter (7.52 mg/l), followed by 7.33 mg/l in Sela and Kyalem Lakes during pre-monsoon, and a minimum of 1.42 mg/l in Kyalem Lake during post-monsoon. Hardness peaked at 15.5 mg/l in Kyalem Lake and at the lowest of 5.12 mg/l in Sela Lake during the monsoon. Conductivity was highest at 39.56  $\mu$ S/cm in Ptso Lake during the monsoon, followed by 17.19  $\mu$ S/cm in Shungatser Lake, and dropped to the lowest 9.28  $\mu$ S/cm in Sela Lake during pre-monsoon. TDS peaked at 35.78 mg/l in Sela Lake during the monsoon, followed by 31.38 mg/l at Kyalem Lake, and dropped to 9.12 mg/l in Shungatser Lake during winter. Temperature exhibited dramatic variation, climbing to 13.61°C in Ptso Lake during the monsoon and plummeting to 1.12°C in Sela Lake during winter, highlighting significant seasonal thermal variation in these aquatic ecosystems (Table 1).

### Composition and distribution of zooplankton

The study recorded 20 zooplankton species belonging to 12 families from three primary groups - Rotifera, Cladocera, and Copepoda, along with a minor presence of Ostracoda in Ptso Lake (Table 2). Rotifers emerged as the most diverse group, contributing nine species (45%) belonging to 5 families, namely Brachionidae (*Brachionus angularis*, *Keratella* sp., *Keratella quadrata*, and *Keratella valga*), Lecanidae (*Lecane* sp. and *Monostyla* sp.), Testudinellidae (*Testudinella patina*), Asplanchnidae (*Asplanchna brightwellii*), and Helvellaceae (*Ascomorpha ovalis*). The Cladocera group comprised six species (25%) belonging to 3 families, viz. Chydoridae (*Alona* sp., *Alona guttata*, and *Chydorus sphaericus*), Bosminidae (*Bosmina* sp. and *Bosmina longirostris*), and Daphniidae (*Daphnia catwaba*). Copepods included four species (20%), belonging to 3 families, viz. Cyclopidae (*Cyclops* sp.), Diaptomidae (*Diaptomus* sp. and *Limnocalanus* sp.), and Canthocamptidae (*Canthocamptus* sp.). Additionally, two species (10%) of the Ostracoda group, belonging to the Cyprididae family (*Cypricercus* sp. and *Cypris* sp.), have been recorded from Ptso Lake.

The distribution of zooplankton varied significantly among the selected HALs. Ptso recorded species belonging to all four major zooplankton groups, i.e., Rotifera (9 species),

Table 1. Seasonal variation of limnological parameters

Lake	Season	Winter	Pre-monsoon	Monsoon	Post-monsoon
Kyalem	pH	8.13	7.83	8.23	7.80
	DO (mg/l)	4.71	6.15	5.20	2.20
	FCO <sub>2</sub> (mg/l)	0.82	0.59	0.67	0.73
	Alkalinity (mg/l)	7.50	7.33	7.20	1.42
	Hardness (mg/l)	12.13	5.50	15.50	10.20
	Conductivity (µS/cm)	11.51	11.77	9.94	9.35
	TDS (mg/l)	14.47	22.78	31.38	21.66
	Temperature (°C)	1.14	5.17	12.11	7.62
Nagula	pH	7.90	7.80	7.50	7.80
	DO (mg/l)	5.18	5.70	7.37	1.61
	FCO <sub>2</sub> (mg/l)	1.24	0.93	0.85	1.36
	Alkalinity (mg/l)	6.78	5.13	6.24	2.36
	Hardness (mg/l)	11.80	10.23	11.20	10.40
	Conductivity (µS/cm)	13.70	11.07	10.55	11.87
	TDS (mg/l)	13.20	19.29	28.41	19.73
	Temperature (°C)	1.27	5.97	12.38	8.21
Ptso	pH	7.86	7.81	7.49	7.57
	DO (mg/l)	5.32	5.69	6.35	3.18
	FCO <sub>2</sub> (mg/l)	0.47	0.62	0.45	0.52
	Alkalinity (mg/l)	6.41	7.31	6.10	3.83
	Hardness (mg/l)	8.40	5.73	7.89	8.20
	Conductivity (µS/cm)	22.97	28.90	39.56	12.10
	TDS (mg/l)	13.10	18.59	23.54	19.66
	Temperature (°C)	1.75	6.79	13.61	8.27
Sela	pH	8.20	8.50	7.94	7.93
	DO (mg/l)	5.23	6.16	6.45	2.07
	FCO <sub>2</sub> (mg/l)	0.55	0.66	0.46	0.53
	Alkalinity (mg/l)	7.52	7.33	7.10	4.50
	Hardness (mg/l)	6.40	5.70	5.12	6.33
	Conductivity (µS/cm)	10.57	9.28	9.85	11.29
	TDS (mg/l)	15.37	25.14	35.78	22.19
	Temperature (°C)	1.12	5.18	12.71	7.56
Shungatser	pH	7.93	7.70	7.54	7.50
	DO (mg/l)	6.43	6.45	6.61	3.05
	FCO <sub>2</sub> (mg/l)	0.51	0.51	0.47	0.51
	Alkalinity (mg/l)	5.13	5.21	4.69	2.33
	Hardness (mg/l)	5.61	5.24	5.12	4.72
	Conductivity (µS/cm)	13.70	15.25	17.19	11.69
	TDS (mg/l)	9.16	18.16	29.31	16.41
	Temperature (°C)	2.23	6.94	13.54	8.78

Cladocera (4 species), Copepoda (3 species), and Ostracoda (2 species). Kyalem and Nagula followed with species from three zooplankton groups each,

including Rotifera (5 species each), Cladocera (4 species each), and Copepoda (2 species each). On the other hand, Sela Lake recorded 4 species of

Table 2. Zooplankton species recorded from the selected HALs

Class/Species	Family
Cladocera	
<i>Alona guttata</i> (Sars)	Chydoridae
<i>Bosmina longirostris</i> (O.F. Müller)	Bosminidae
<i>Chydorus sphaericus</i> (O.F. Müller)	Chydoridae
<i>Daphnia catawba</i> (Coker)	Daphniidae
<i>Alona</i> sp.	Chydoridae
Copepoda	
<i>Cyclops</i> sp.	Cyclopidea
<i>Diaptomus</i> sp.	Diaptomidae
<i>Canthocamptus</i> sp.	Canthocamptidea
<i>Limnocalanus</i> sp.	Diaptomidae
Rotifera	
<i>Asplanchna brightwellii</i> (Gosse)	Asphanchidae
<i>Ascomorpha ovalis</i> (Bergendal)	Helvellaceae
<i>Brachionus angularis</i> (Gosse)	Brachionidae
<i>Keratella quadrata</i> (Müller)	Brachionidae
<i>Keratella valga</i> (Ehrenberg)	Brachionidae
<i>Testudinella patina</i> (Hermann)	Testudinella
<i>Keratella</i> sp.	Brachionidae
<i>Lecane</i> sp.	Lecanidae
<i>Monostyla</i> sp.	Lecanidae
Ostracoda	
<i>Cypricercus</i> sp.	Cyprididae
<i>Cypris</i> sp.	Cyprididae

Copepoda and 3 species each of Rotifera and Cladocera, and Shungatser Lake recorded 5 species of Cladocera, 3 species of Rotifera, and 2 species of Copepoda (Fig. 2).

### Seasonal abundance

The study revealed a distinct seasonal pattern of zooplankton abundance in the HALs. The zooplankton abundance was low during winter. However, the species belonging to Cladocera (*Alona guttata*, *Chydorus sphaericus*, and *Bosmina longirostris*) showed relatively higher numbers in Kyalem, Ptso, and Shungatser. During pre-monsoon, *Ascomorpha ovalis* (Rotifera) was abundant in Ptso, while *Chydorus sphaericus*, *Bosmina longirostris* (Cladocera), and *Cyclops* sp. (Copepoda) were common in most HALs. The monsoon season supports high abundances of Rotifers (*Keratella valga* and *Brachionus angularis*), Cladocerans (*Alona guttata*), and Cyclopoids (*Cyclops* sp.) in

Kyalem, Ptso, and Sela. Notably, *Limnocalanus* sp. (Copepoda) was exclusively recorded in Ptso during the monsoon season. Zooplankton abundance declined during the post-monsoon season compared to the monsoon; however, it was higher than in winter for species like *Lecane* sp. (Rotifera) and *Alona guttata* (Cladocera) at Kyalem and Sela. Various environmental factors, including water temperature, nutrient availability, and hydrological regimes, could be attributed to the seasonal variations in zooplankton abundance, which act as drivers shaping the dynamics of these aquatic communities (Table 3).

### Diversity indices

Diversity indices reflect the seasonal variations. The Shannon-Wiener diversity index peaks at 2.816 (monsoon) and 2.515 (winter) in Ptso Lake. It ranged from 2.223 (post-monsoon) to 2.351 (pre-monsoon) at Kyalem Lake, from 1.870 (winter) to 2.250 (monsoon) at Nagula Lake, from 2.014 (winter) to 2.238 (pre-monsoon) at Sela Lake, and from 2.338 (winter) to 2.481 (post-monsoon) at Shungatser Lake. Dominance index ranged between 0.093 (monsoon) to 0.112 (winter) at Ptso Lake, 0.127 (pre-monsoon) to 0.202 (post-monsoon) at Kyalem Lake, 0.177 (monsoon) to 0.268 (winter) at Nagula Lake, 0.148 (pre-monsoon) to 0.216 (winter) at Sela Lake, and 0.165 (monsoon) to 0.228 (winter) at Shungatser Lake. Evenness index ranged between 0.956 (post-monsoon) to 0.972 (monsoon) at Ptso Lake, 0.953 (post-monsoon) to 0.976 (monsoon) at Kyalem Lake, 0.915 (winter) to 0.975 (monsoon) at Nagula Lake, 0.946 (winter) to 0.970 (monsoon) at Sela Lake, and 0.951 (post-monsoon) to 0.967 (monsoon) at Shungatser Lake (Table 4). The studied lakes exhibited distinct ecological dynamics across seasons. Diversity indices show peak values during the monsoon and pre-monsoon seasons, with the highest diversity at Ptso Lake and a wide range of variation at Nagula Lake. Dominance was higher during winter, while evenness showed a more uniform species distribution during the monsoon.

### Cluster analysis

To determine the similarities in physico-chemical properties of the HALs, Bray-Curtis cluster analysis was performed. The results were presented as dendrograms showing percentages. The investigation

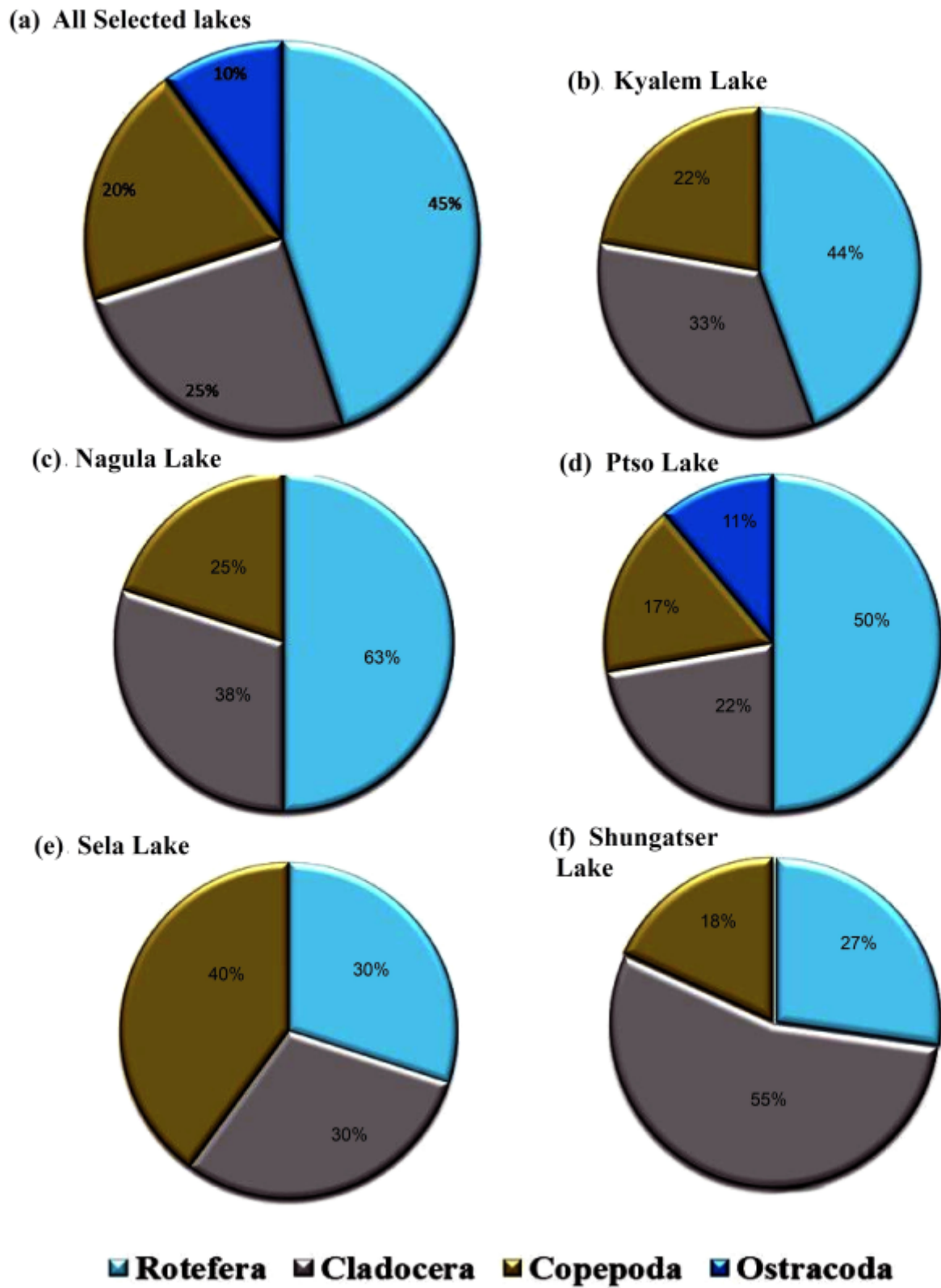


Figure 2. Composition of zooplankton in the selected HALs

Table 3. Seasonal abundance of zooplankton species

HALs	Class	Species	W	PR	M	PM
Kyalem	Cladocera	<i>Alona guttata</i>	+	+	++	+++
		<i>Bosmina longirostris</i>	+	++	++	+
		<i>Chydorus sphaericus</i>	+	++	++	+
	Copepoda	<i>Alona</i> sp.	+	++	+	+
		<i>Cyclops</i> sp.	-	++	-	+
		<i>Diaptomus</i> sp.	+	++	+++	+
	Rotefera	<i>Keratella valga</i>	+	++	++	-
		<i>Keratella</i> sp.	+	++	++	+
		<i>Lecane</i> sp.	+	+	++	++
		<i>Brachionus angularis</i>	+	++	++	+
Nagula	Cladocera	<i>Alona guttata</i>	+	+	++	+
		<i>Bosmina longirostris</i>	-	+	++	+
		<i>Chydorus sphaericus</i>	+	+	+	+
	Copepoda	<i>Cyclops</i> sp.	+	+	+	+
		<i>Diaptomus</i> sp.	-	+	++	+
	Rotefera	<i>Keratella valga</i>	+	+	++	+
		<i>Keratella</i> sp.	+	+	+	+
		<i>Lecane</i> sp.	+	-	+	+
		<i>Brachionus angularis</i>	-	+	+	+
		<i>Monostyla</i> sp.	+	+	+	+
Ptso	Cladocera	<i>Alona guttata</i>	+	-	+	+
		<i>Bosmina longirostris</i>	+	+	+	+
		<i>Daphnia catwaba</i>	+	+	++	+
		<i>Alona</i> sp.	+	++	++	++
	Copepoda	<i>Cyclops</i> sp.	+	++	+++	++
		<i>Diaptomus</i> sp.	+	+	+	+
		<i>Limnocalanus</i> sp.	-	-	+	+
	Rotefera	<i>Keratella valga</i>	+	++	+++	++
		<i>Keratella</i> sp.	+	++	+++	+
		<i>Lecane</i> sp.	+	++	++	+
<i>Brachionus angularis</i>		+	++	+++	++	
<i>Keratella quadrata</i>		+	++	+++	+	
<i>Testudinella patina</i>		+	+	++	+	
<i>Asplanchna brightwellii</i>		-	+	+	+	
<i>Monostyla</i> sp.		+	+	+	+	
Ostracoda	<i>Ascomorpha ovalis</i>	-	+++	+	++	
	<i>Cypricercus</i> sp.	+	+	++	-	
	<i>Cypris</i> sp.	+	+	++	+	
Sela	Cladocera	<i>Alona guttata</i>	+	++	+++	++
		<i>Bosmina longirostris</i>	+	++	+++	++
		<i>Chydorus sphaericus</i>	+	++	++	+
	Copepoda	<i>Canthocamptus</i> sp.	+	+	+	+
		<i>Limnocalanus</i> sp.	+	++	+++	+
		<i>Cyclops</i> sp.	+	++	+++	++
		<i>Diaptomus</i> sp.	+	+	++	++
	Rotefera	<i>Keratella valga</i>	-	+	++	+
		<i>Keratella</i> sp.	-	+	+	+
		<i>Lecane</i> sp.	++	++	+	+++
Shungatser	Cladocera	<i>Alona guttata</i>	+	+	+	+
		<i>Chydorus sphaericus</i>	+	+	+	+
		<i>Chydorus</i> sp.	+	+	+	+
		<i>Bosmina longirostris</i>	-	++	+	+
		<i>Chydorus sphaericus</i>	+	-	+	+
	Copepoda	<i>Cyclops</i> sp.	+	+	++	+
		<i>Diaptomus</i> sp.	+	+	+	+
	Rotefera	<i>Keratella valga</i>	+	+	++	+
		<i>Keratella</i> sp.	+	+	+	+
		<i>Lecane</i> sp.	-	+	+	+

+++ = Abundant, ++ = Common, + = Rare, - = Absent, W = Winter, PR = Pre-monsoon, M = Monsoon, PM = Post-monsoon

Table 4. Diversity, dominance, and evenness indices

HALs	Season	Diversity	Dominance	Evenness
Kyalem	Winter	2.305	0.170	0.971
	Pre-monsoon	2.351	0.127	0.968
	Monsoon	2.328	0.133	0.976
	Post-monsoon	2.223	0.202	0.953
Nagula	Winter	1.870	0.268	0.915
	Pre-monsoon	2.058	0.204	0.943
	Monsoon	2.250	0.177	0.975
	Post-monsoon	2.214	0.190	0.963
Ptso	Winter	2.515	0.112	0.971
	Pre-monsoon	2.683	0.115	0.967
	Monsoon	2.816	0.093	0.972
	Post-monsoon	2.716	0.100	0.956
Sela	Winter	2.014	0.216	0.946
	Pre-monsoon	2.238	0.148	0.966
	Monsoon	2.236	0.160	0.970
	Post-monsoon	2.236	0.160	0.970
Shungatser	Winter	2.338	0.228	0.962
	Pre-monsoon	2.395	0.180	0.960
	Monsoon	2.408	0.165	0.967
	Post-monsoon	2.481	0.226	0.951

showed similar relationships between different seasons. The dendrograms have been generated in groups of clusters by reducing the dimensionality of the large datasets. The cluster analysis indicated significant similarities across all four seasons, with 75-100% similarity. The highest similarity was observed between pre-monsoon and winter (91.2%), followed by monsoon and pre-monsoon (87.5%), and winter and post-monsoon (91.2%). The lowest similarity was found between post-monsoon and monsoon (76.8%). The analysis revealed no direct comparisons between non-adjacent seasons, such as post-monsoon and winter, monsoon and winter, or pre-monsoon and post-monsoon. Hence, the results highlighted a gradual change in the environmental conditions as the season progresses into the next (Fig. 3).

### Correlation coefficient

A Pearson's correlation coefficient ( $r$ ) analysis was conducted to examine the relationship among the physico-chemical properties of water. The results revealed a positive correlation between conductivity and TDS ( $r=0.946$ ,  $p<0.01$ ), indicating a proportional

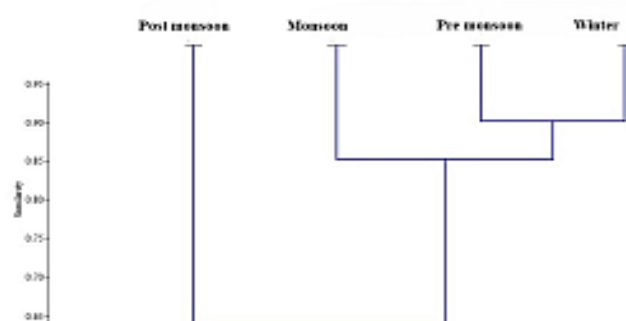


Figure 3. Cluster analysis of limnological properties of lakes

increase in both. A significant positive correlation between alkalinity and DO ( $r=0.697$ ,  $p<0.01$ ) was also observed, suggesting an association between higher alkalinity levels and increased DO concentrations. Further, a positive correlation between  $\text{FCO}_2$  and hardness ( $r=0.604$ ,  $p<0.05$ ) indicates a corresponding increase in both  $\text{FCO}_2$  and hardness. On the other hand, pH exhibited a moderate positive correlation with alkalinity ( $r=0.505$ ,  $p<0.05$ ) and a mild negative correlation with temperature ( $r=-0.479$ ,  $p<0.05$ ), indicating that higher pH values are

Table 5. Pearson's correlation coefficient of limnological variables

Variables	pH	DO	FCO <sub>2</sub>	Alk	H	C	TDS	Temp
pH	1.000	0.027	0.100	0.505*	0.172	-0.289	-0.366	-0.479*
DO	0.027	1.000	-0.297	0.697**	-0.173	0.416	0.251	0.100
FCO <sub>2</sub>	0.100	-0.297	1.000	-0.145	0.604**	-0.318	-0.285	-0.213
Alkalinity	0.505*	0.697**	-0.145	1.000	0.056	0.233	0.153	-0.229
Hardness	0.172	-0.173	0.604**	0.056	1.000	-0.244	-0.186	-0.012
Conductivity	-0.289	0.416	-0.318	0.233	-0.244	1.000	0.946**	0.163
TDS	-0.366	0.251	-0.285	0.153	-0.186	0.946**	1.000	0.133
Temp	-0.479*	0.100	-0.213	-0.229	-0.012	0.163	0.133	1.000

\*. Correlation is significant at 0.05 level (2-tailed), \*\*. Correlation is significant at 0.01 level (2-tailed). Alk = Alkalinity, C = Conductivity DO = Dissolved oxygen, FCO<sub>2</sub> = Free carbon dioxide H = Hardness, TDS = Total dissolved solids, Temp = Temperature

associated with increased alkalinity and negatively associated with temperature. Other parameters were statistically not significant (Table 5).

#### Canonical correspondence analysis (CCA)

To understand the relationship between the physico-chemical properties of water and zooplankton species in the selected HALs, the CCA method was applied. The CCA was drawn from 20 zooplankton taxa and eight physico-chemical properties. At Kyalem Lake, axis 1 explained 47.77% and axis 2 explained 44.41% of the association. The distribution and abundance of *Chydorus sphaericus* were primarily influenced by TDS, DO, conductivity, and alkalinity. Hardness determined the abundance of *Brachionus angularis* and *Monostyla* sp., while pH was correlated with *Diatomus* sp. Similarly, *Alona* sp. was closely associated with DO. Other species, such as *Cyclops* sp., *Alona guttata*, *Lecane* sp., *Keratella valga*, etc., are merely associated with the selected physico-chemical variables of the lakes (Fig. 4a).

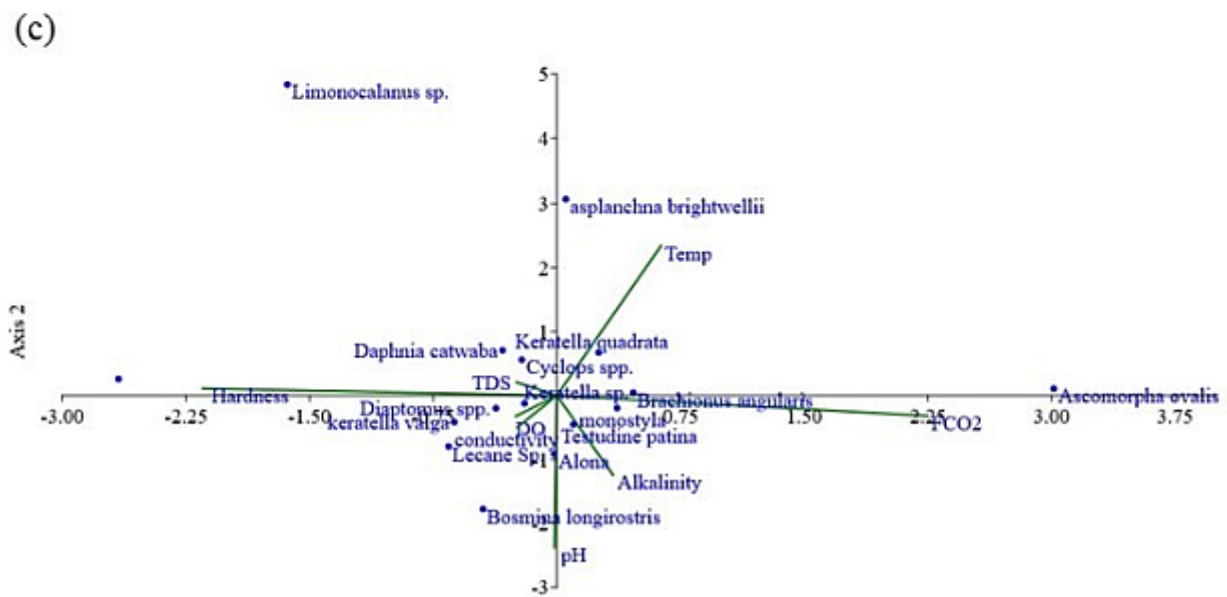
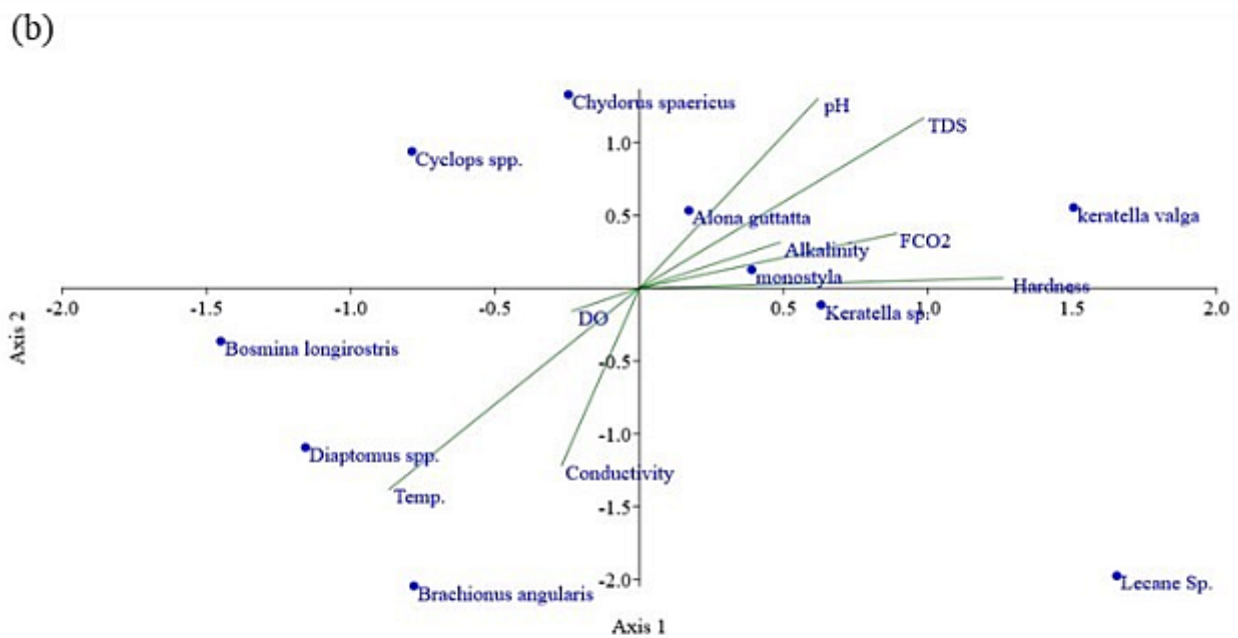
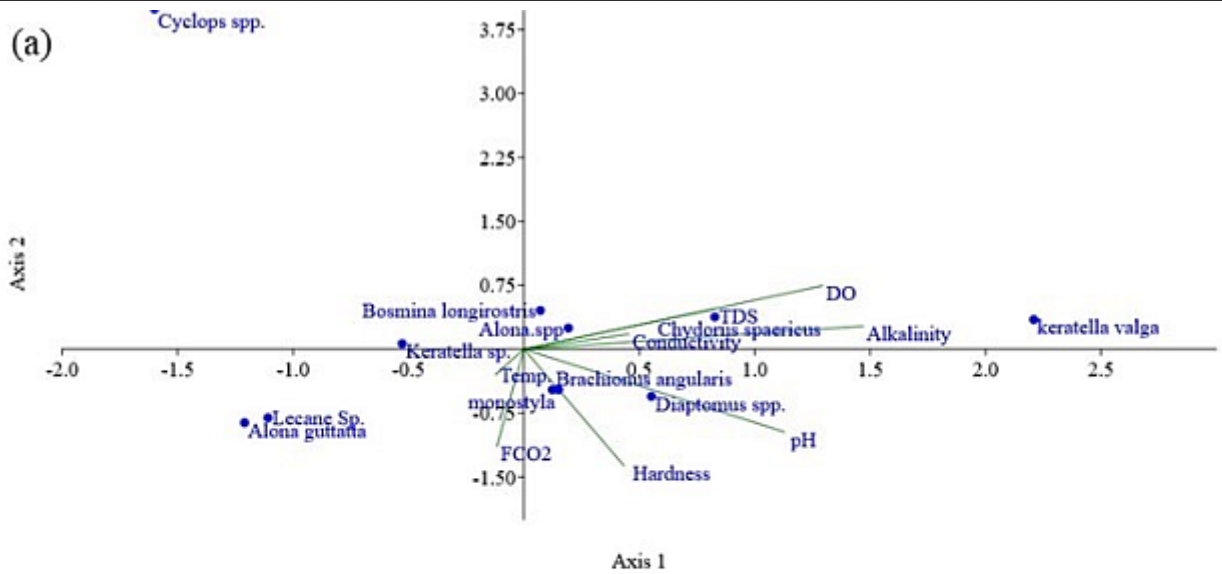
At Nagula Lake, axis 1 explained 67.15% of the association while axis 2 explained 26.45%. The pH and TDS are closely associated with the distribution of *Alona guttata*. Alkalinity and FCO<sub>2</sub> influence the presence of *Monostyla* sp., *Keratella* sp. is correlated with hardness, and *Diatomus* sp. is correlated with water temperature. *Cyclop* sp., *Bosmina longirostris*, *Lecane* sp., *Keratella valga*, etc., are not associated with the selected parameters (Fig. 4b)

The CCA of Ptso Lake showed that 71.15% of the correlation was explained by axis 1 and 14.12%

by axis 2. DO, conductivity, and pH determine the distribution of *Keratella* sp., *Lecane* sp., *Diatomus* sp., and *Alona* sp. FCO<sub>2</sub> was associated with *Monostyla* sp. and *Brachionus angularis*; TDS with *Cyclop* sp.; temperature with *Keratella valga*; alkalinity with *Testudinella patina*, and hardness with *Diatomus* sp. Species like *Limnocalanus* sp. *Asplanchna brightwell* and *Ascomorpha ovalis* were rarely associated with the physico-chemical variables (Fig. 4c).

In the case of Sela Lake, the CCA shows that 68.59% of the correlation was explained by axis 1 and 22.54% by axis 2. The distribution of *Canthocamptus* sp. was influenced by hardness and FCO<sub>2</sub>, while *Alona guttata* was closely associated with water temperature. Similarly, the distribution of *Cyclops* sp. was influenced by conductivity, while *Diatomus* sp. was associated with TDS. On the other hand, *Bosmina longirostris*, *Keratella valga*, *Keratella* sp., and *Lecane* sp. were rarely correlated with environmental parameters (Fig.4d).

Lastly, the CCA analysis of Shungatser Lake revealed that 67.29% of the association was elucidated by axis 1 and 25.78% by axis 2. The hardness, FCO<sub>2</sub>, and pH were positively correlated with *Diatomus* sp., whereas the distribution of *Alona guttata* was influenced by alkalinity, DO, and conductivity. *Lecane* sp. and *Cyclops* sp. were associated with temperature and other species, such as *Bosmina* sp. *Keratella valga*, *Chydorus* sp. *Chydorus sphaericus*, etc., were not affected by the physico-chemical parameters (Fig. 4e).



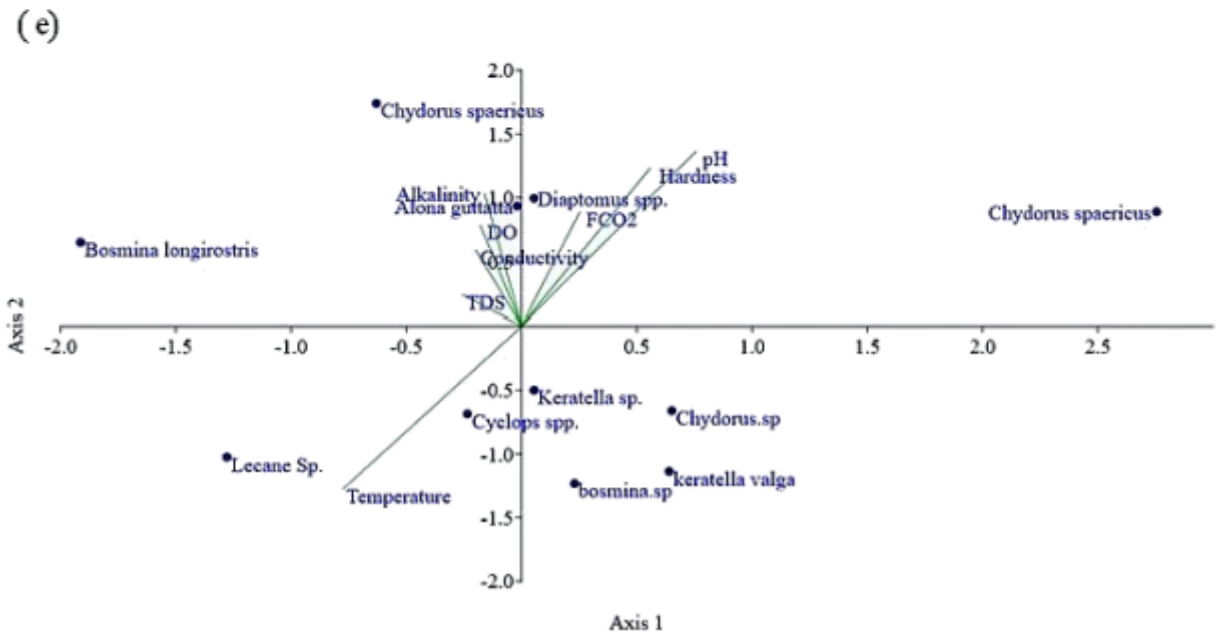
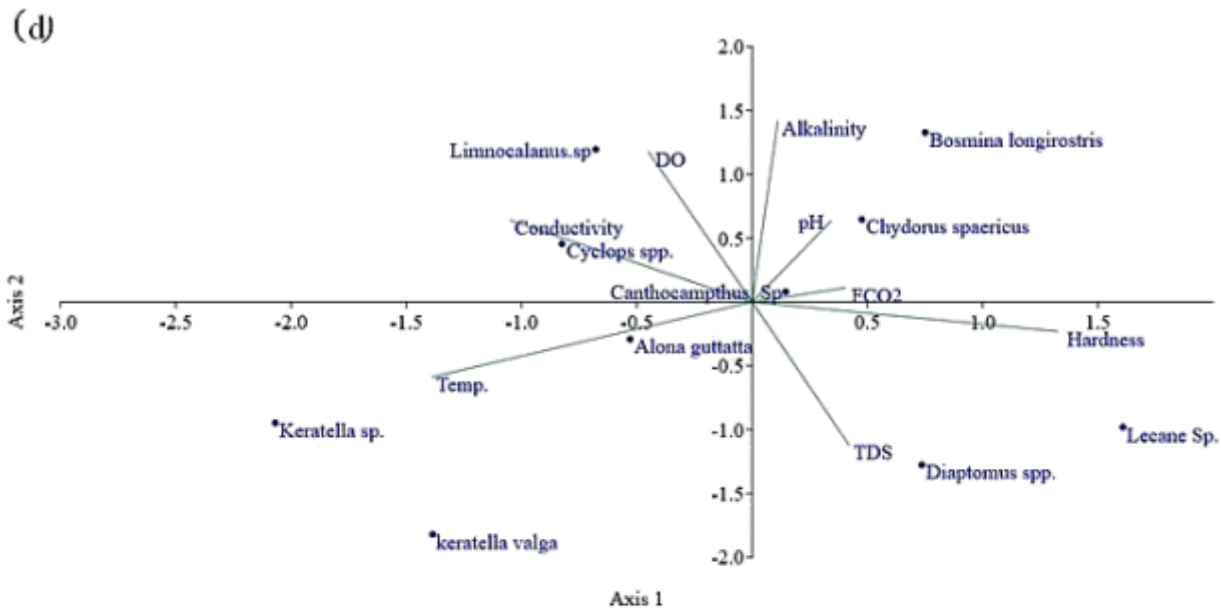


Figure 4. Canonical correspondence analysis. (a) Kyalem Lake, (b) Nagula Lake, (c) Ptso Lake, (d) = Sela Lake, (e) = Shungatser Lake

**DISCUSSION**

The physico-chemical analysis of HALs revealed distinct seasonal variations among the parameters. The Himalayan lakes exhibit distinct physico-chemical characteristics across seasons, with water temperatures varying significantly. Water temperature in the study area peaks during monsoon (12.10-13.78°C) and remains lowest in winter (1.0-3.0°C), in agreement with previous studies (Panwar

and Malik 2014, Hassan et al. 2015, Sultan et al. 2023). The extremely low winter temperatures result from reduced atmospheric temperatures and snow cover, which limit water turbulence, heat exchange, and light penetration (Felip et al. 2002), thereby creating heterotrophic systems (Pastorino and Prearo 2020). The lakes maintain consistently alkaline pH levels (7.4-8.6) (Kaushik et al. 2021, Thapa et al. 2024) with effective buffer capacity (Ghimire et al. 2013), where increased pH may result from reduced

photosynthetic activity and carbon dioxide/bicarbonate assimilation (Bhateria and Jain 2016). Dissolved oxygen concentrations fluctuate seasonally (1.60-7.47 mg/l), showing higher levels during monsoon and pre-monsoon periods due to the influence of various environmental factors (Singh et al. 2017, Thapa et al. 2024). Total alkalinity remains relatively low (1.41-7.53 mg/l) and affects photosynthesis and phytoplankton growth through limited carbon dioxide availability (Raju et al. 2014).  $\text{FCO}_2$  levels remain at the minimal levels (0.44-1.39 mg/l), with some lakes showing negligible values due to optimal temperature and photosynthesis conditions (Coole 1979, Pant et al. 2017, Sharma and Kumar 2017). Total hardness (1.41-7.53 mg/l) and TDS (4.0-21.0 mg/l) remain consistently low, indicating snowmelt as the primary water source (Deka et al. 2015) as hardness is primarily influenced by calcium and magnesium concentrations (Mallick 2017). Conductivity measurements range from 7.58 to 41.42  $\mu\text{S}/\text{cm}$ , suggesting low ion concentrations (Upadhyay et al. 2012, Sultan et al. 2023). Statistical analysis revealed strong positive relationships between TDS and conductivity ( $r=0.946$ ) (Sharma and Tiwari 2018), pH and alkalinity ( $r=0.505$ ), and DO with total alkalinity ( $r=0.697$ ) (Hassan et al. 2015), while pH demonstrated a negative correlation with temperature ( $r=-0.479$ ) (Kumari and Sharma 2019).

Zooplankton are important biotic components as they mediate the link between phytoplankton and fish and play a key role in the cycling of organic materials in aquatic ecosystems (Schriver et al. 1995, Lomartire et al. 2021). They stand at the base of food webs and biogeochemical cycles and live in all aquatic environments (D'Alelio 2019). The richness, abundance, variation, and diversity of zooplankton can be used to assess water quality and management practices (Kar and Kar 2013). The zooplankton diversity in the selected HALs revealed a complex ecological representation with 20 species belonging to Rotifera, Cladocera, Copepoda, and Ostracoda (only Ptso Lake). Similar zooplankton compositions have been reported from other Himalayan lakes (Pandit et al. 2016, Antal et al. 2020, Singh and Samartha 2021, Mehra and Arya 2022, Kumari et al. 2023). The study found Rotifers to be dominant, accounting for 45% of the species. Many previous

studies have also reported the dominance of Rotifera (Raina and Vass 1993, Sharma 2011, Kumar et al. 2012, Sharma and Kumari 2018, Sharma and Noroh 2020, Singh et al. 2021).

The highest number of zooplankton species was recorded in Ptso, and the lowest in Shungatser Lake. A distinct seasonal pattern in zooplankton species abundance was observed in the studied HALs. Seasonal fluctuations in zooplankton populations are well known, as they exhibit bimodal oscillations in spring and autumn in temperate lakes (Wetzel 2001). The abundance of zooplankton was highest during the monsoon season, a phenomenon documented in different aquatic environments from marshes to estuaries and coastal regions (Venrick 2012, Rajaneesh et al. 2018, Benedetti et al. 2019). Rotifers like *Keratella valga* and *Brachionus angularis*, Cladocera like *Alona guttata*, and Copepods like *Cyclops* sp. and *Diaptomus* sp. were found abundant during the monsoon season. Interestingly, *Limnocalanus* sp. was exclusively recorded in Sela during this productive period. On the other hand, zooplankton abundance was lowest in the winter season across most groups (Mansano et al. 2013, Melo and Medeiros 2013). The decrease in zooplankton abundance during the winter season can be attributed to changes in environmental conditions, resource availability, and biotic interactions (Grover and Chrzanowski 2006, Benedetti et al. 2019, Moura et al. 2020, Rossano et al. 2020). However, even during this harsh period, certain hardy *Cladoceran* species, such as *Alona guttata*, *Chydorus sphaericus*, and *Bosmina longirostris*, maintained relatively higher numbers in Kyalem, Ptso, and Shungatser Lakes, suggesting their adaptive capabilities to withstand the winter conditions. The marked seasonal variations in zooplankton abundance and composition underline the dynamic nature of HALs and their sensitivity to environmental changes throughout the year.

The application of quantitative measures revealed significant spatial and temporal variation across zooplankton groups in the HALs. The species diversity values peaked during the monsoon at Ptso, particularly for Rotifera. Shungatser recorded the highest diversity of Cladocera during the monsoon, while Sela recorded the highest diversity of Copepoda. The dominance patterns varied across

lakes, with some showing high dominance in certain groups during specific seasons, suggesting dynamic community structures responding to various environmental changes. The evenness values indicated balanced communities, especially during monsoons.

The CCA results revealed an intricate relationship between zooplankton species and the physico-chemical parameters. Conductivity, DO, and pH emerged as key factors influencing the distribution of zooplankton species in conformity with previous studies (Chakraborty and Das 2015, Hu et al. 2019, Shen et al. 2021), including *Keratella* sp., *Lecane* sp., and *Diatomus* sp. across multiple lakes (Akbulut 2004). TDS was strongly associated with *Chydorus sphaericus* in Kyalem and *Alona guttata* in Nagula. Water hardness played a significant role in determining the abundance of *Brachionus angularis* and *Monostyla* sp. (Basavaraj and Kadadevaru 2023) in Kyalem, and *Canthocamptus* sp. in Sela. The presence and relative abundance of Rotifers and Copepods have been reported to serve as sensitive indicators, reflecting underlying water chemistry and trophic status (Attayde and Bozelli 1998, Leonardi et al. 2020). Furthermore, alkalinity and FCO<sub>2</sub> were associated with *Monostyla* sp. in Nagula and *Diatomus* sp. in Shungatser. Likewise, water temperature was closely associated with *Alona guttata* in Sela and *Lecane* sp. in Shungatser.

## CONCLUSIONS

The study revealed an intricate interplay between seasonal environmental factors and aquatic community dynamics in the HALs of Tawang district. Monsoons were the most ecologically active season, fostering maximum diversity and abundance of zooplankton, while winters presented a period of ecological dormancy with significantly reduced biotic activity. Rotifera emerged as the dominant zooplankton group, underscoring its adaptability to fluctuating conditions. Statistical analyses, including CCA, revealed that conductivity, DO, and alkalinity are key water parameters shaping zooplankton community structure. These HALs, with diverse zooplankton species, are vital for maintaining regional biodiversity and ecosystem functions. However, their vulnerability to climatic shifts and

anthropogenic influences underscores the need for targeted conservation strategies. This research establishes a foundational understanding of the ecological dynamics of HALs in Tawang, paving the way for future studies and effective measures to conserve these critical freshwater resources.

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**Authors' contributions:** DB conceived the ideas, designed the methodology, collected the data, and prepared the original manuscript draft. GN supervised, reviewed, and edited the draft manuscript. Both authors read the manuscript and approved it for publication.

**Conflict of interest:** Authors declare no conflict of interest.

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