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Plankton Community Composition: Disentangling The Roles of Environmental Parameters and PFAS

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SYDVATTEN

Abstract

This study elucidated the complex drivers influencing plankton community structure in Lake Bolmen, a critical freshwater resource for drinking water production. The study investigated the relative contributions of per- and polyfluoroalkyl substances (PFAS) and a suite of environmental parameters (pH, water temperature, dissolved oxygen, conductivity, turbidity, chlorophyll, total dissolved solids, salinity, total nitrogen, and total organic carbon) on the phytoplankton and zooplankton community composition in Lake Bolmen. By analyzing PFAS concentrations, a range of environmental parameters, and plankton community composition from nine sites, the study found that both environmental factors and PFAS significantly determine plankton community composition. While PFAS concentrations were strongly correlated with salinity, they did not show significant correlations with any other of the measured water quality parameters. Principal Component Analysis (PCA) and Canonical Correspondence Analysis (CCA) revealed specific relationships between environmental parameters and PFAS with various plankton genera, indicating their preferences for certain conditions. Specifically, the plankton genera *Pinnularia, Tabularia, Pediastrum, Stauroneis*, *Aphanizomenon flosaquaqe, Scendesmus, Dinobyron, Gymnozya*, *Synedra capitata, Synura and Chydorus* are showing strong association with the PFAS and environmental parameters. The study underscores the necessity of integrated environmental assessments, considering both traditional water quality parameters and emerging contaminants like PFAS, to effectively monitor and manage lake ecosystem health.

Keywords: Plankton community, Abiotic factors, Community composition, Multivariate analysis, Aquatic Health

1. Introduction

1.1 Background

Plankton communities include both phytoplankton and zooplankton and the proper monitoring of the plankton diversity is important as it plays a crucial role in the functioning of whole lake ecosystems (Geng et al., 2022). As primary producers in lakes, phytoplankton biomass, composition, and abundance affect the quality of water by enhancing the amount of dissolved oxygen and by reducing the concentration of carbon dioxide in water, thus regulating the pH of the water. The algal presence also shows a vital role in the energy transfer and in the release of essential nutrients to the ecosystem (McCormick and Cairns, 1994). Zooplanktons also play a vital part in aquatic food webs by transferring organic matter and energy from the lower trophic levels to higher trophic levels and ultimately to larger predators, such as fish (Pascariello et al., 2019).

Phytoplankton and zooplankton diversity in lakes depends on several physical, chemical and biological factors and the plankton responds to changes in environmental conditions by changing their behavior, abundance and composition (Geng et al., 2022). Behavioral changes like alterations in feeding rates and food selectivity occurred in copepods due to the change in nutrient concentration in its environment (Sailley et al., 2015). Abiotic factors such as dissolved oxygen, temperature, pH, conductivity and nutrient composition in the lake water control growth, diversity and ecological functioning of the plankton community (Kondowe et al., 2022). Temperature is considered as one of the most important factors regulating the phytoplankton community because it significantly alters the composition among other ecological parameters (Wang et al., 2015). Nutrient concentration is also influencing the plankton community composition, for example large amount of silica uptake during spring blooms lead to the dominance of diatoms among phytoplankton community (Brown et al.,2003). Zooplankton abundance can also be altered by other environmental parameters such as water temperature, dissolved oxygen, pH, conductivity, turbidity, nitrate, phosphate, chlorophyll a and salinity and its abundance and composition are essential for monitoring the condition of aquatic system (Abdul et al., 2016).

Wide varieties of natural and human-made substances are entering into the aquatic environment both through natural and artificial pathways, severely affecting the stability of aquatic ecosystem (Zhou et al., 2025). Overall ecosystem functioning of lake environments is connected to the changes in water quality in connection with the changes in surrounding land use (Leech et al., 2018). In addition to the organic contaminants, persistent chemical contaminants like PFAS are also released into the aquatic system which eventually bioaccumulate in different trophic levels (Pascariello et al., 2019). Long perfluorocarbon chains in PFAS have higher binding property with sediments and this leads to its bioaccumulation of PFAS in aquatic organisms as well as in humans (Åkerblom et al., 2017). PFAS are persistent chemical substances used widely in various applications such as firefighting foams, paints, cosmetics and industrial process like textiles and paper (Buck et al., 2011). An increased concentration of PFAS is seen near military bases and airports where firefighting training activities are conducted and also near the wastewater treatment plants (Sunderland et al., 2019; Remucal et al., 2019). Among the PFAS compounds, PFOS are considered as the major contaminant seen in aquatic environment, which can cause harmful effects on aquatic organisms (Podder et al., 2021; Simpson et al., 2021).

Monitoring of environmental parameters as well as the presence of contaminants in the water of Lake Bolmen is important to avoid the health risk for human beings by direct consumption as drinking water. In addition, Lake Bolmen is important for recreation and fishing. Changes in phytoplankton and zooplankton community composition may affect higher trophic food web levels both in terms of species composition and abundance, thus affecting recreational and professional fishing. In addition to this, humans can be exposed to chemical contaminants through trophic transfer by consuming fish. As basal level of the food web, the effects of PFAS on the composition of plankton communities are therefore important to examine.

1.2 Aim

This thesis aims to understand the importance of PFAS and environmental factors in shaping the plankton community composition of Lake Bolmen.

1.3 Research Questions

1. Are PFAS concentrations important in determining the plankton community composition of Lake Bolmen?
2. Are Environmental parameters important in determining the plankton community composition of Lake Bolmen.
3. Are PFAS concentrations significantly correlated to the measured abiotic water quality parameters.

2. Methods

2.1 Research Design

This study is conducted at 9 different locations around Lake Bolmen. Location include Storån, Lillån, Önnekvarn, Byholma, Kafjorden (K2), Lillsjön, Murån, Piksborg and Skeen. The Bolmen Research Station belonging to Sydvatten AB provided the PFAS concentration from each site at different points in time. Sampling dates for PFAS concentration were on October of 2023, March, May and August of 2024 and January and February of 2025 but all sites were not sampled during all these times. The data regarding the PFAS concentration and its corresponding sampling dates are summarized in Appendix A. Environmental parameters such as pH, water temperature, dissolved oxygen (DO), conductivity, turbidity, chlorophyll, total dissolved solids (TDS) and salinity were additionally measured for this study during the sampling of planktons. Both phytoplankton and zooplankton samples were taken February 2025 for evaluating the plankton composition. All sampling were done according to the protocol.

2.2 Study Area

Lake Bolmen is the largest lake in southern Sweden covering three counties such as Kronoberg, Jönköping and Halland with a surface area of 184 km² (Borgstörm, 2020). Figure 1 shows the satellite image of Lake Bolmen showing the 9 sites of this study and highlighted the military base located near its catchment area, which can be a source of persistent chemical contaminants like PFAS.

Figure 1. Satellite image of Lake Bolmen marking the 9 sites of this study and highlighted area(pink) shows the area of military base.

2.3 Sampling Procedure

In this study, field sampling for plankton and environmental parameters was performed at nine different sites around Lake Bolmen in February 2025. The sampling time, latitude and longitude coordinates of the sampling sites were recorded. A 150 ml of water samples was collected from each site for taking the measurements of environmental parameters. A multiparameter YSI EXO2 was used to determine pH, water temperature, dissolved oxygen (DO), salinity, total dissolved solids (TDS), turbidity, chlorophyll a and conductivity at each sampling site. Plankton samples were collected using plankton net. The zooplankton sampling was done using a plankton net of mesh size 65µm and the phytoplankton sampling was done with plankton net of mesh size 20 µm. After sampling, the plankton samples were stored in dark 150 ml bottles and fixed using lugol's iodine solution for further analysis. All the parameters measured in the field were recorded properly. After reaching the laboratory, all samples were kept in the refrigerator at 4˚C for further analysis.

Waters samples for PFAS analyses were collected according to standard methods (United States Environmental Protection Agency, 2020). The collected samples were sent to SGS Analytics Sweden accredited laboratory in Linköping for analyses of 26 PFAS-groups in Lake Bolmen according to the Swedish drinking water regulations (LIVSFS 2022:12) for raw water for drinking water production. Only the total concentration of PFAS was used in this study.

2.4 Laboratory Analysis

The collected samples were analysed in the Rydberg Laboratory for Applied Science, Halmstad University according to standard methods. For measuring absorbance, firstly each sample were mixed well and then transferred to a small vial of 20 ml using syringe filtration with a filter having a pour size of 0.45 µm. Absorbance was analysed using a UV visible spectrophotometer (UV-1900i UV-VIS Spectrophotometer, Shimadzu, Tokyo, Japan) at a wavelength of 420nm. Total Nitrogen and Total Organic Carbon were measured on unfiltered samples using a Total organic carbon analyzer (TOC-

L, Shimadzu, Tokyo, Japan) and Total nitrogen measuring unit (TNM-L, Shimadzu, Tokyo, Japan) in unfiltered water sample.

Taxonomic analysis of plankton species were done based on databases (Sandhall and Berggren, 1997; John et al., 2002) and the abundance of plankton samples were done using microscope (YS2-H, Nikon, Japan). The phytoplankton samples were counted under 100 x magnification and zooplankton samples were counted under the 40 x magnification. One hundred individuals per sample were counted and determined to the lowest possible taxonomic level to obtain a reliable estimate of species/taxon composition of the plankton community.

2.5 Data Analysis

Collected data were tabulated in excel. Average of the PFAS concentration in each site at different dates were calculated. As the total number of zooplankton individuals in per sample was less than 100, the proportionate composition of zooplankton species was calculated in percentage by dividing the number of individuals per species by the total number of zooplankton counted and multiplied by 100. For phytoplankton, the total number of individuals counted and identified per sample was 100, therefore each species count already represented this species proportionate contribution in percent.

2.6 Statistical analysis

For analysis, we used the statistical tools such as IBM SPSS Statistics (Version: 28.0.0(190)) and PAST ver.4.09 software. To visualize the relationship of environmental parameters and PFAS with plankton community, firstly a correlation based principal component analysis (PCA) was performed using the environmental parameters and PFAS from 9 different sites to identify which of the variables had the highest influence over the plankton community (Zhu et al., 2012). Positive or negative association with eigenvectors greater than 0.65 were considered as important for the analysis.

The principal components obtained from the PCA analysis were used for the canonical correspondence analysis (CCA) to identify the influence of environmental parameters and PFAS in plankton species composition (Zhu et al., 2012). Finally, a Pearson correlation was done to find the correlation between PFAS concentration and water quality parameters. Statistical significance was set to $P < 0.05$.

3. Results

3.1. Environmental parameters

The average of the PFAS concentration observed from 9 different sites of Lake Bolmen at different periods showed that the PFAS concentration was highest in Lillsjön area (27.1 ng/l) and lowest in Lillån (2.93 ng/L) and Önnekvarn area (3.09 ng/L) (Fig.2). The environmental variables such as pH, water temperature, dissolved oxygen (DO), conductivity, turbidity, chlorophyll, total dissolved solids (TDS) and salinity were measured. (Table.1). Among these environmental parameters absorbance, total nitrogen and total organic carbon showed a visible variation at different sites. (Fig.3a-c). The PFAS concentrations at different sites of Lake Bolmen showed a strong significant negative correlation with salinity (pearson correlation(r) = -0.731 p = 0.025) but were not correlated with other water quality parameters.

Table 1. *This data represents the measurements of field and laboratory analyses. PFAS (Per-and polyfluoroalkyl substances), TN (Total Nitrogen), TOC (Total Organic Carbon), Abs (Absorbance), Turb (Turbidity), Cond (Conductivity), TDS (Total Dissolved Solids), Temp (Temperature), Chl a(Chlorophyll a), DO (Dissolved Oxygen) and pH are presented here.*

Site	Coordinates	PFAS (ng/l)	TN (mg/l)	TOC (mg/l)	Abs	Turb (FNU)	Cond (µs/cm)	TDS (mg/l)	Sal (PSU)	Temp (°C)	Chl a (µg/l)	DO (mg/l)	pH
Storån	57.08203N 13.73266E	4.523	1.296	18.8	0.092	2.65	44.4	47	0.03	4.849	1.82	12.04	7.53
Lillån	57.08068N 13.72609E	2.932	1.374	16.82	0.094	9.36	53.8	59	0.04	3.606	4.03	11.51	7.4
Önnekvarn	56.89285N 13.56162E	3.093	0.758	12.72	0.06	1.21	36.3	40	0.03	3.402	1.49	12.61	7.78
Bhylom	56.79995N 13.58342E	18.60	0.686	13.32	0.049	1.28	37.7	40	0.03	4.99	1.53	11.9	7.52
K2	56.76055N 13.66653E	10.43	0.636	13.01	0.047	1.07	39.8	42	0.03	4.745	2.05	12.66	7.81
Lillsjön	56.78986N 13.62671E	27.05	1.01	33.81	0.22	3.03	31.5	32	0.02	6.08	3.84	12.06	5.62
Murån	56.78353N 13.64013E	11.63	0.781	17.62	0.093	2.7	42.1	43	0.03	6.076	3.67	11.02	6.2
Piksborg	56.78754N 13.64600E	15.15	0.540	12.1	0.058	0.75	39.7	43	0.03	4.154	1.69	12.82	7.77
Skeen	56.76200N 13.67049E	4.603	0.036	13.18	.127	0.85	39.1	40	0.03	5.894	2.14	12	7.74

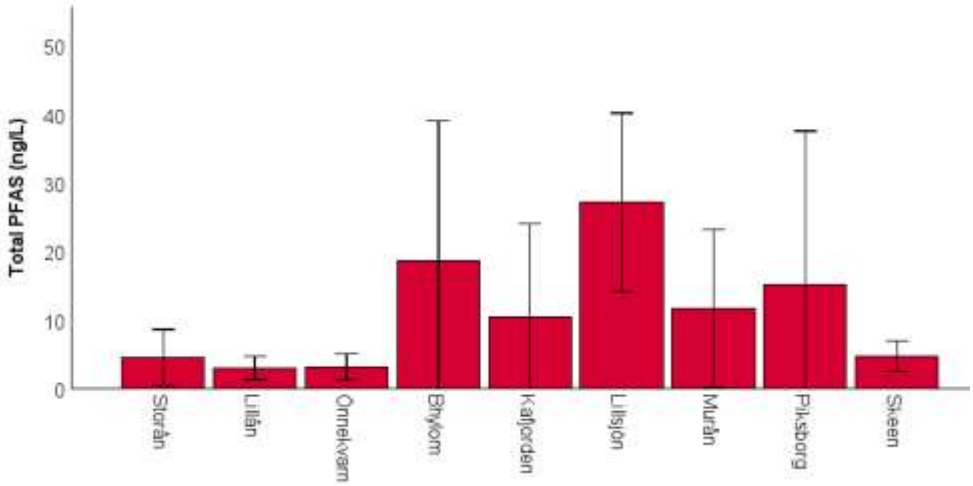


Figure 2. Bar graph showing the average of PFAS concentrations measured from 9 different sites of Lake Bolmen at different periods. Whiskers represent the standard error.

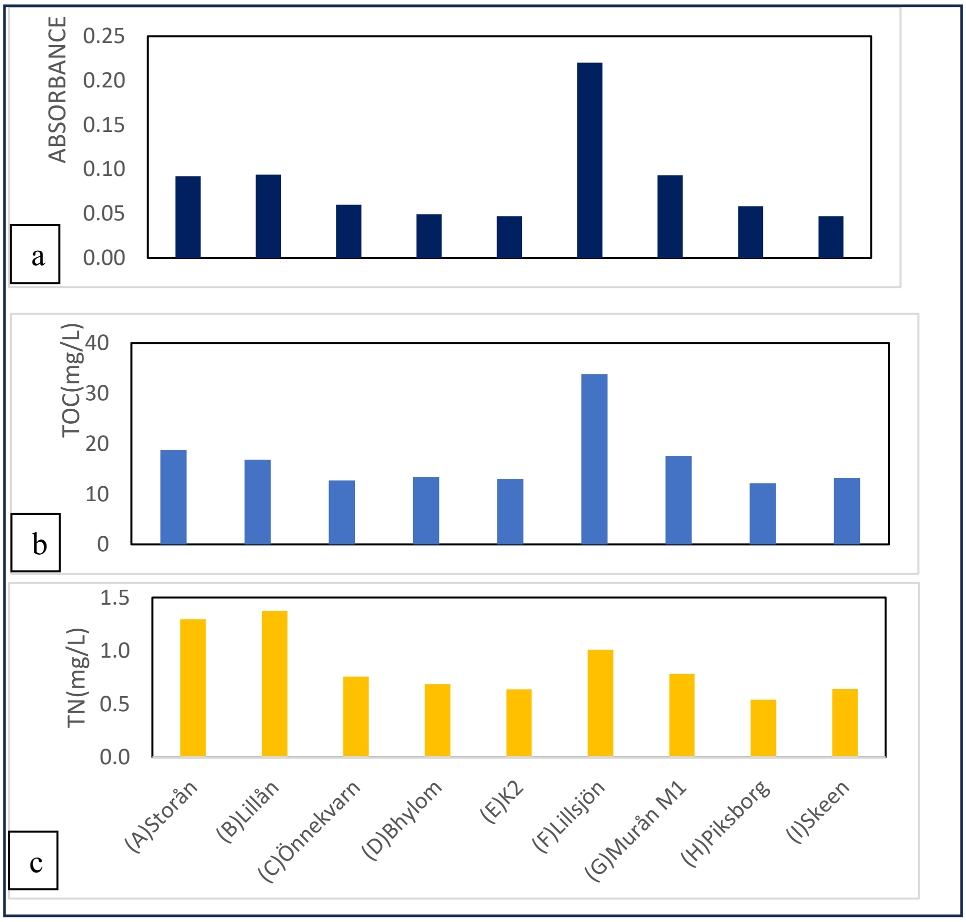
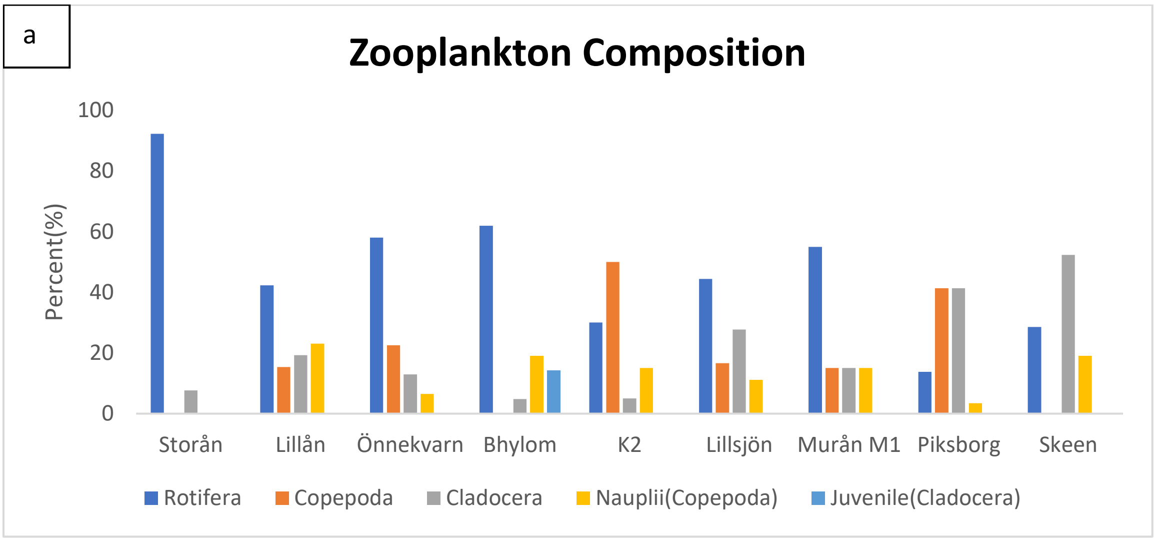


Figure 3. Bar graph showing (a) Absorbance (b)Total Organic Carbon and (c) Total Nitrogen from the 9 different sampling sites around Lake Bolmen. One measurement for each variable was conducted for each site.

3.2. Plankton Composition

Rotifera, copepoda and cladocera are the zooplankton groups noted in this study along with the nauplii of copepods and juveniles of cladocerans. Among the zooplankton groups, rotifers was the most dominant group at all sites with an average proportion contribution of 47.38 % ± 22.97 %, followed by cladocera, copepoda, nauplii of copepods and juveniles of cladocera (Fig.4a) Phytoplankton community comprises the groups diatomaphycea, chrysophyceae, cyanophyceae and chlorophycea, in which diatomaphycea was the most dominant group at all sites with an average number of 64.44% ± 17.36 % (Fig. 4b).



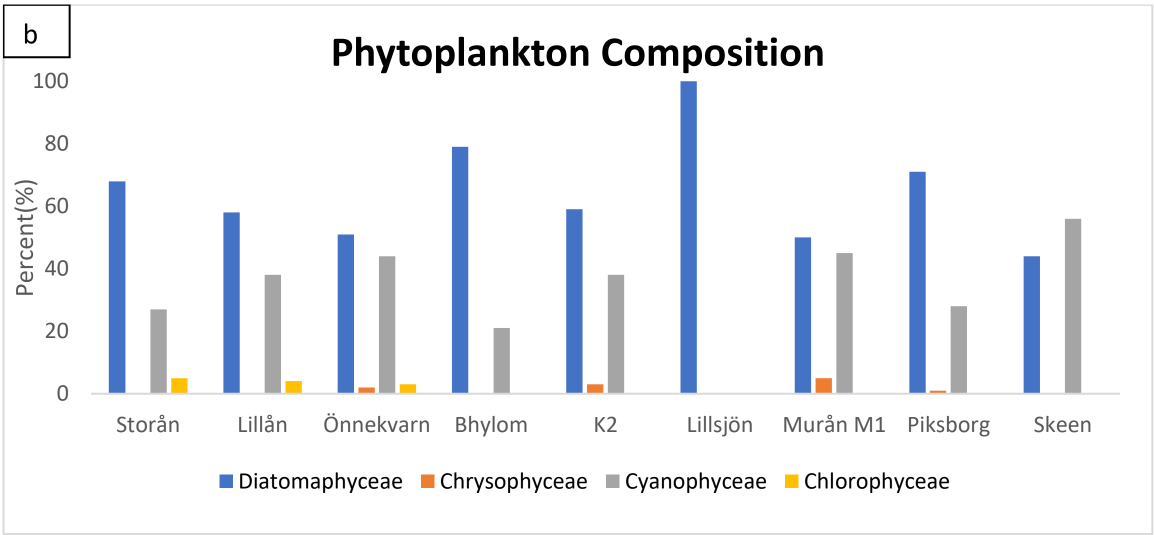


Figure 4.(a) Zooplankton composition (b) Phytoplankton composition at the 9 different sampling sites around Lake Bolmen. One sample was analysed for each site.

Among the zooplankton community, Rotifera group comprises the genus *Keratella, Kellicotia, Ascomorpha* and *Testudinella*, cladocerans include the genera *Bosmina, Daphnia* and *Chydorus.*

The phytoplankton group Diatomaphycea comprises the species and genera *Asterionella formosa, Tabellaria fenestrate*, *Melosira, Navicula, Tabellaria flocculosa, Fragilaria crotonensis, Suirella ovata, Synedra capitata, Tabularia, Pinnularia, Stauroneis* and *Nitzschia acicularis*. The phytoplankton groups Chrysophyceae includes the genera *Synura* and *Dinobyron;* Chlorophycea consists of the genera *Scenedesmus, Gymnozyga, Staurastrum, Pediastrum* and *Stauodesmus* and Cyanophyceae comprises the genera and species *Microcystis, Oscillatoria* and *Aphanizomenon flosaquae*.

3.3. Relationship Between PFAS, Environmental Parameters and Plankton Communities

From the Principal Component Analysis, four components were extracted with a cumulative variance of 94.9%, which also met the criterion of having eigenvalues greater than 1. Principal component (PC) 1 showed a total variance of 44.2% and was positively associated with conductivity, total dissolved solids and salinity. And also, PC1 was negatively associated with PFAS and temperature. (PC) 2 showed 32.7% of total variance and was positively associated with TN, TOC, absorbance, turbidity and chlorophyll and negatively associated with pH. (PC) 3 showed 12.9% of total variance and was positively associated with dissolved oxygen. (PC) 4 showed 5.1% of total variance and has no association with any original variables (Table 2).

***Table 2**. This data is the result of principal component analysis on environmental variables and PFAS measured at different sites. Bold digits indicate high r-values and the variables with these highlighted r-values show strong association with corresponding principal components (PC) 1*

Original variable	**PC1**	**PC2**	**PC3**	**PC4**
PFAS	**-.803**	.204	-.027	.448
TN	.382	**.764**	.308	-.343
TOC	-.608	**.735**	.275	-.102
Absorbance	-.564	**.755**	.330	-.015
Turbidity	.561	**.792**	.120	.143
Conductivity	**.908**	.359	-.105	-.014
TDS	**.944**	.298	-.001	.049
Salinity	**.977**	.036	-.154	.127
Temperature	**-.680**	.262	-.543	-.276
Chlorophyll	-.039	**.917**	-.100	.174
DO	-.083	-.558	**.748**	.035
PH	.625	**-.734**	.115	-.064

CCA was performed to analyze the relationship of PFAS and environmental parameters with plankton community (Fig. 5). A total of 3 PCs were chosen for CCA based on its association to the original variable. The first axis (p=0.011) and third axis (p=0.012) in CCA ordination plot were significant. PC1 showed a strong effect on the phytoplankton such as diatomophyceae (*Pinnularia, Tabularia,* and *Stauroneis*) and chlorophyceae (*Pediastrum)* which are likely to thrive in cold waters with low PFAS contamination. The phytoplankton like diatomophyceae (*Navicula, Asterionella formosa)* and zooplankton group rotifera (*Testudinella)* are abundant in warm waters with higher PFAS concentrations and favour areas with lower conductivity, total dissolved solids and salinity. PC2 correlates positively to phytoplanktons such as cyanophyceae (*Aphanizomenon flosaquaqe),* chlorophyceae (*Scendesmus, Gymnozya) and* chrysophyceae (*Dinobyron)* and which prefers nutrient-rich, potentially more turbid and slightly acidic waters with high algal production. PC3 showed a positive effect on phytoplanktons comprising diatomophyceae (*Synedra capitata),* and chrosophyceae (*Synura),* also on zooplankton group *cladocerans(Chydorus)* and Juveniles of cladocerans which could imply an association with an environment having even high dissolved oxygen. Phytoplankton communities are influenced by almost all the abiotic factors including PFAS, temperature, salinity, dissolved oxygen, conductivity, nutrients, pH, turbidity and chlorophyll a. Zooplanktons also shows association with these factors except the nutrients, pH, turbidity and chlorophyll a.

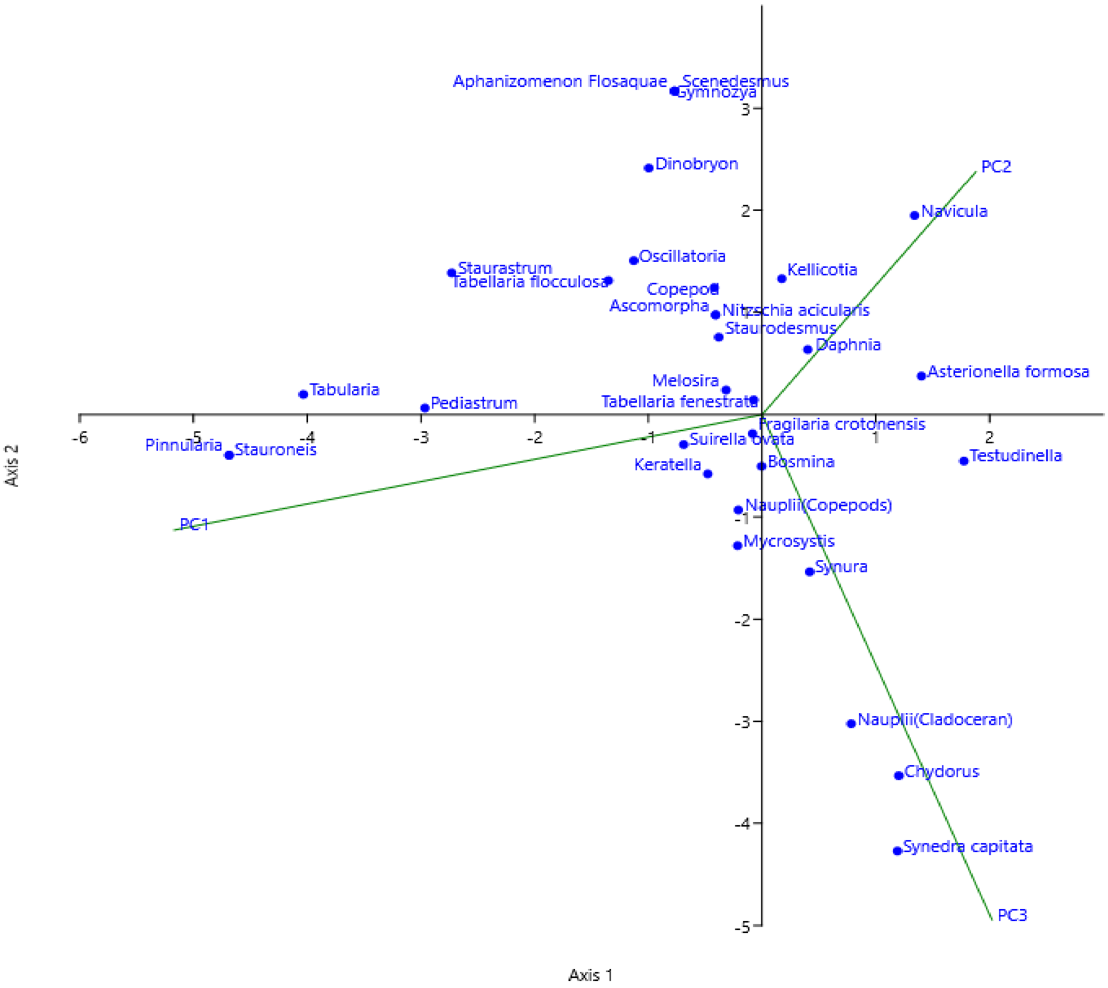


Figure 5. CCA plot based on the plankton species composition and the three principal components. Species that appear near to the centre of the ordination plot are moderately affected by the PC's. Pinnularia, Tabularia, Pediastrum, Stauroneis, Navicula, Asterionella Formosa, Testudinella, Aphanizomenon flosaquaqe, Scendesmus, Dinobyron, Gymnozya, Synedra capitata, Chydorus, Nauplii of cladocerans and Synura are the species that are strongly affected by the PCs.

4. Discussion

From the results of the study, we can state that the plankton community composition in the lake Bolmen appears to be strongly influenced by both the environmental parameters such as temperature, turbidity, conductivity, pH, total dissolved solids, absorbance, chlorophyll, salinity, total nitrogen and total organic carbon and by the presence of PFAS. Kondowe et al. (2022) found that there is a significant influence of parameters such as dissolved oxygen, temperature, pH, conductivity and nutrient availability in shaping plankton diversity and abundance. Temperature is considered the key regulator of phytoplankton community structure by influencing metabolic rates, nutrient uptake kinetics and stratification dynamics (Wang et al., 2015; Sommer et al., 2012). Phytoplankton like Cyanophyceae and Chlorophyceae as well as the rotifers of zooplankton community in Shengjin Lake of eastern China shows a strong dependence on high nutrient levels especially total nitrogen based on the type of vegetation in the catchment area (Zhou et al., 2025). In addition, the total nitrogen was strongly influencing the composition of phytoplankton in freshwater reservoirs (Znachor et al., 2020).

CCA analysis of the study revealed that the phytoplankton community is majorly influenced by chemical and physical parameters and also by nutrients, but the zooplanktons were not influenced by nutrients, they are influenced more by physical parameters, followed by chemical parameters. In contrary to our study, Geng et al. (2022) show that nutrient parameters are more strongly influencing the composition of zooplankton community composition than the phytoplankton community composition. The study of Akindele and Olutona (2014) states that turbidity, dissolved oxygen and temperature showed a positive relationship with the zooplankton abundance and composition while the total dissolved substances showed a negative relationship with the same which is slightly different from our result.

Our investigation did not reveal a significant correlation between total PFAS concentration and the measured water quality parameters except salinity. Yin et al. 2022 showed that, the solubility of PFAS in water can decrease with the increase in the ionic strength of water through a phenomenon of salting out effect. Anthropogenic pollutants affect the conductivity of water and the variation in conductivity influence the composition of zooplankton communities (Wu et al., 2017). Persistent organic pollutants like PFAS have the potential to affect the zooplankton communities through bioaccumulation (Pascariello et al., 2019). The study by Davis et al. (2024) shows that phytoplankton such as blue green algaes are seriously affected by the PFAS exposure, which in turn altered the nutrient availability.

The limitations of this study are that the sampling period is during the late winter, which affects the sampling of plankton communities especially in the case of zooplanktons. Also, PFAS concentration was measured during different time periods but the environmental parameters and plankton community composition were taken only once for this study. Sampling period may affect the plankton community composition, so it would have been better to do sampling in different seasons. Increasing light and nutrient availability together with the increased water temperature on summer season enhance the growth of phytoplankton and it rapidly increases the zooplankton communities especially cladocerans and copepods (Temponeras at al., 2000). Seasonal flooding of the lake can affect the zooplankton composition, cladocerans are dominating in rainy seasons while rotifers replaced the cladoceran population in summer environment (Okogwu, 2010).

In determining the ecological integrity of lake ecosystems, this study is significant because it helps to disentangle the relative influence of anthropogenic contaminants and natural environmental factors. This study highlights the importance of abiotic factors in structuring the plankton community, which highlights the necessity of effective monitoring and management techniques which consider basic water quality criteria in order to preserve ecosystem health. The significance of an integrated approach to environmental assessment is further highlighted by this study, which shows that contaminants like PFAS may have more complex or indirect effects even though there are no direct connections with the water quality. To improve risk assessment and conservation efforts, future studies should combine high resolution ecological data with extensive pollutant analysis to better predict the long-term effects of various stressors on these significant ecosystems.

5. Conclusion

We found that both environmental parameters and PFAS concentration in Lake Bolmen are determining phytoplankton and zooplankton community composition. Based on this finding, we can conclude that the plankton species in Lake Bolmen that are most closely linked to the two influencing factors can serve as biological indicators. *Pinnularia, Tabularia, Stauroneis, Pediastrum*, *Navicula, Asterionella formosa* and *Testudinella* are planktons influenced by the presence of contaminant PFAS and also by the change in water quality parameters such as temperature, conductivity, salinity and total dissolved solids. Total organic carbon, total nitrogen, turbidity, pH and chlorophyll a are influencing the phytoplanktons *Aphanizomenon flosaquaqe, Scendesmus, Dinobyron and Gymnozya*. Alterations in the concentration of dissolved oxygen affects the composition of the phytoplankton *Synedra capitata and Synura* and zooplankton *Chydorus* and Nauplii of cladocerans This study also revealed that there is no significant correlation between PFAS and majority of the environmental factors except salinity. In order to examine the shift in relationship between plankton communities, environmental parameters, and PFAS, it would be useful to extend this study by carrying out more sample during other seasons than late winter or early spring.

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APPENDIX

Appendix A: Overview of PFAS concentration (ng/l) in different sites at different sampling dates

Site	20-10-2023	01-03-2024	16-05-2024	22-08-2024	29-01-2025	03-02-2025	24-02-2025
Storån	7.72	5.07	0.78	-	-	-	-
Lillån	4.08	4.69	1.5	1.46	-	-	-
Önnekvarn	3.23	4.71	1.34	-	-	-	-
Bhylom	-	-	-	-	8.41		28.8
Kafjorden	-	-	-	-	-	3.67	17.2
Lillsjön	-	16.51	25.75	38.9	-	-	-
Murån	8.08	5.82	3.95	28.7	-	-	-
Piksborg	-	-	-	-	3.99		26.32
Skeen	5.11	6.25	2.45	-	-	-	-