SEASONAL VARIATIONS OF PHYTOPLANKTON IN RELATION TO ENVIRONMENTAL INFLUENCES IN THE SOUTHERN MEDITERRANEAN (TONGA LAKE, NORTHEAST ALGERIA)

BENSAFIA, N.[1,2] – DJABOURABI, A.[2,3] – AOUADI, A.[4] –AMIRA, A. B.[5] – ABDALLAH, K. W.[1*] – TOUATI, H.[2] – BENSOUILAH, M.[2]

[1]Biodiversity and Ecosystem Pollution Laboratory, Marine Sciences Department, Faculty of Natural and Life Sciences, Chadli Bendjedid University, B.P 73, 36000 El-Tarf, Algeria (https://orcid.org/0009-0006-5305-1655 (Bensafia, N.), https://orcid.org/0000-0002-7036-5043 (Abdallah, K. W.))

[2]Laboratory of Ecobiology of Marine and Littoral Environments, Marine Sciences Department, Faculty of science, Badji Mokhtar – Annaba University P.O. Box 12, Annaba 23000, Algeria (https://orcid.org/0000-0003-0696-5826 (Djabourabi, A..), https://orcid.org/0000-0002-4185-5449 (Touati,H.), https://orcid.org/0000-0002-9574-5915 (Bensouilah. M.))

[3]Functional and evolutionary ecology laboratory, Biology Department, Faculty of Natural and Life Sciences, Chadli Bendjedid University, B.P 73, 36000 El-Tarf, Algeria

[4]Laboratory Agriculture and Ecosystem Functioning, Biology Department, Faculty of Natural and Life Sciences, Chadli Bendjedid University, B.P 73, 36000 El-Tarf, Algeria (https://orcid.org/0000-0002-3259-7396 (Aouadi, A.))

[5]Marine Sciences Department, Faculty of science, Badji Mokhtar – Annaba University P.O. Box 12, Annaba 23000, Algeria (https://orcid.org/0000-0002-5095-7711 (Amira, A. B.))

*[*]Corresponding author
e-mail: abdallahkhadidjawissal@gmail.com*

(Received 21st Oct 2024; accepted 4th Feb 2025)

Abstract. The spatial and temporal dynamics of phytoplankton communities were examined in relation to environmental characteristics in Tonga Lake, situated in the Southwestern Mediterranean (Algeria). Monthly samples were collected from November 2021 to October 2022 at two key locations: one near the sluices and another at the centre of the lake. The study assessed the taxonomic composition, abundance, and diversity index of phytoplankton. A total of 43 genera of phytoplankton were identified within the lake. Notably, diatoms were predominant, with 24 genera identified, compared to 12 genera of Cyanobacteria and 7 genera of Dinoflagellates, highlighting seasonal shifts in these taxa. During the summer months, the community was primarily composed of *Aphanizomenon sp., Nostoc sp., Asterionella sp., Planktothrix sp., Dinophysis sp., Cyclotella sp.,* and *Tropidoneis sp*., correlating with elevated concentrations of ammonium (NH_4), chlorophyll-*a* (Chl-*a*), and temperature (T°). Conversely, the spring season was marked by the prevalence of *Stauroneis, Achnanthes, Cymbella, Anomoeneis, Gomphonema, Mastogloia, Navicula, Nitzschia, Peridinium,* and *Surirella*. Additionally, autumn showed a significant presence of *Diatoma sp., Gyrodinium sp., Diploneis, Pinnularia,* and *Lyngbya sp*.

Keywords: *phytoplankton, nutrients, diatoms, Mediterranean, monitoring, Tonga Lake*

Introduction

Wetlands are among the most diverse and productive ecosystems on Earth (Ramachandra and Solanki, 2007). They are characterized by a unique interplay of factors, including water, soil, plants, animals, nutrient cycling, groundwater recharge, surface-atmosphere water exchange, and species diversity (Akil et al., 2014; Haddad and Ghoualem, 2014). These ecosystems are of paramount importance, harboring an incredible diversity of life forms and playing a vital role in maintaining ecological balance.

At the heart of these ecosystems, phytoplankton emerges as a key player in the food chain and overall productivity. Composed of photosynthetic microorganisms (Revathy and Krishnakumar, 2018), phytoplankton is responsible for primary production, regulating the carbon cycle, and oxygenating water bodies. This makes them a crucial link in the ecosystem and a valuable biological indicator for monitoring and assessing water quality and the health of aquatic ecosystems (Tiwari and Chauhan, 2006; Laskar and Gupta, 2009).

The composition and distribution of aquatic organisms are generally determined by the spatio-temporal dynamics of the environment. Plankton communities exhibit variations in species composition and abundance across biotopes with different hydrological and physicochemical parameters (Skála, 2015; Voutilainen et al., 2016). Phytoplankton communities are sensitive to any changes in their aquatic environment (Bhat et al., 2015; Dory et al., 2024). Their structure and diversity in aquatic systems are attracting growing interest among researchers, as they provide crucial information on the health of these ecosystems and their resilience to environmental changes (Geethu and Balamurali, 2018; Gu et al., 2024). Understanding the species composition, spatial distribution, and interactions within phytoplankton communities can reveal valuable insights into water quality, nutrient gradients, and abiotic and biotic factors influencing their development (Barton et al., 2013; Zhang et al., 2024).

Moreover, according to Hamaidi-Chergui et al. (2014), phytoplankton populations exhibit seasonal variations and are influenced by both physical and chemical factors in the water. Similarly, Djerboua et al. (2022) demonstrated that phytoplankton populations and their distribution are linked to abiotic conditions, vary with the seasons, and are influenced by physicochemical factors such as pH and temperature. Concurrently, Bharati et al. (2020) found significant correlations between the abundance of different phytoplankton communities and factors like temperature, depth, transparency, pH, and alkalinity.

Tonga Lake, located in the El-kala National Park (northeastern Algeria), is a wetland site registered as part of a biogeographic complex renowned for its biological diversity. This lake provides an ideal setting for studying phytoplankton diversity due to its varied abiotic conditions. Abiotic factors such as temperature, light, nutrient availability, and pH can influence the growth, composition, and spatial distribution of phytoplankton in this lake.

Several ecological studies have been conducted to analyze the relationships between the structure of phytoplankton communities and environmental variability in different aquatic systems in northeastern Algeria. These studies include the work of Draredja et al. (2019) in the El-Mellah lagoon, Touati et al. (2019) in the El-Mellah Lagoon, Charifi et al. (2019), and Saoudi et al. (2017) who focused on cyanobacterial populations, and Heramza et al. (2021) who studied diatoms in the Aïn Dalia dam. The only study to have comprehensively examined the ecology of these microorganisms in Tonga Lake is that of Djabourabi et al. (2017) and Bensafia et al. (2020) whose objective was to characterize the physicochemical parameters and evaluate the trophic state of this water body.

The current study aims to contribute to the understanding of phytoplankton communities in Tonga Lake by characterizing their taxonomic composition over a one-year period in two representative stations. The study will also conduct a comprehensive inventory of these organisms and explore the links between their dynamics and key environmental parameters to identify the factors determining their distribution.

Methodology

Study area

Located within a natural site that is part of the El Kala National Park in the extreme northeast of Algeria (36° 51' 511" N - 8° 30' 100" E), Tonga Lake is a shallow water body, classified as a "pond," with a depth of less than 6 meters. It is situated approximately 5 kilometers southeast of the city of El Kala and 65 kilometers southeast of the city of Annaba. The lake connects to the sea via the artificial channel of Messida. It encompasses a total free water surface area of around 2300 hectares, which significantly decreases during the summer months due to evaporation. The lake is fed by numerous tributaries, with the most significant being El Hout Wadi and Messida Wadi (*Fig. 1*).

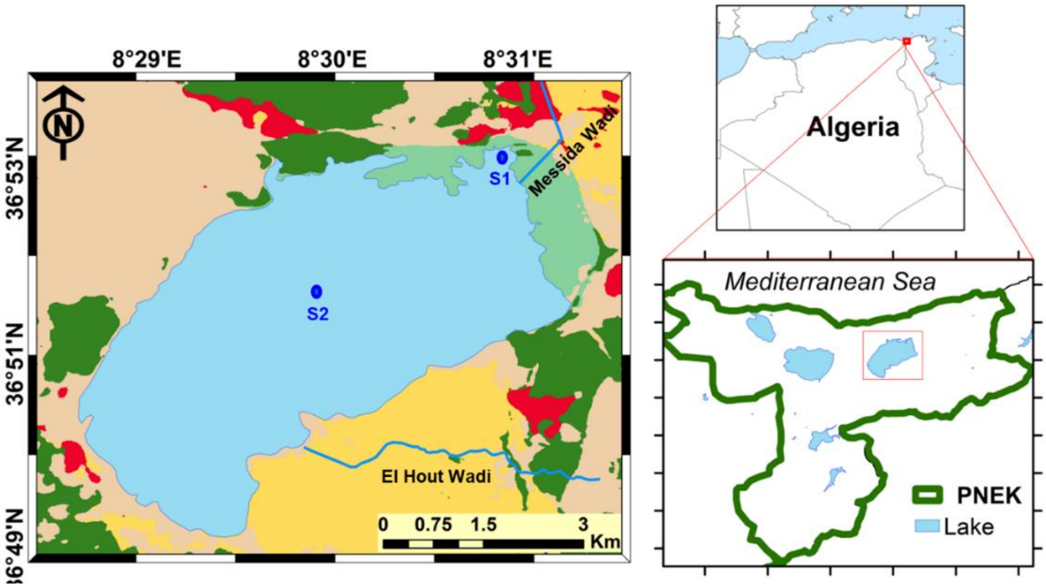

Figure 1. *The study area and location of sampling stations in Tonga Lake (southern Mediterranean Sea)*

Additionally, it receives groundwater from the underlying aquifer in the surrounding land. Samples were collected monthly from November 2021 to October 2022 at two representative stations: the first near the sluices and the second at the center of the lake (*Fig. 1*).

Physical and chemical parameters

The physical measurements and analyses of water were conducted at approximately 50 cm below the surface. Parameters such as temperature, pH, and dissolved oxygen were directly measured on-site monthly using a multiparameter instrument equipped with various probes (Consort, 535). Additionally, nutrient concentrations (nitrite (NO_2), nitrate (NO_3), phosphate (PO_4) and ammonium (NH_4)) were determined in the laboratory using colorimetric methods (Aminot and Chaussepied, 1983). In this study, the selected nutrients had a limiting effect on the spatiotemporal dynamics of phytoplankton within the sampling site. These nutrients play a crucial role in the distribution and abundance of phytoplankton populations.

Regarding the Chl-*a*, the pigment was extracted in darkness at 4 °C for 24 hours using a 90% acetone solution after filtering the lake water, and subsequently quantified using the monochromatic method of Lorenzen (1967). The concentrations of suspended matter (SPM) were measured following the method outlined by Aminot and Chaussepied (1983).

Phytoplankton sampling and processing

In parallel with the measurements of physicochemical parameters, phytoplankton samples were collected from the surface waters by filtering a volume of 50 L through a plankton net with a mesh size of 20 µm. The composition of the phytoplankton communities was based on the microscopic observation of preserved samples (10% formaldehyde), enabling the identification of the main taxa based on their morpho-anatomical characteristics, with reference to the identification keys provided by Bourrelly (1985) and Couté (1995). The counting of phytoplankton cells was performed according to the method established by Andresen Leitao et al. (1982). An OPTIKA optical microscope is employed for the identification of the species.

Diversity parameters

Several diversity indices were calculated including: Total abundance (TA): which is the total number of individuals; Species richness (S): corresponding to the total number of species; Shannon index: defined as

$$H' = -\sum(Pi \times \log 2Pi) \tag{Eq.1}$$

where Pi represents the proportion of individuals belonging to each species in relation to the total number of individuals (N). The Shannon diversity index (H') varies from zero when only one species is present, and reaches its maximum when all species are present in equal proportions (Shannon, 1948). Relative abundance (RA) was calculated using the formula:

$$Pi = \left({}^{n_i}/_{N}\right) \times 100 \tag{Eq.2}$$

where n_i is the number of individuals of species i and N is the total number of individuals of all species.

$$H_{max} = \log 2S \tag{Eq.3}$$

representing the maximum value of the Shannon diversity index (H') for a given number of species. In addition, the evenness index (E) was calculated by dividing the Shannon and Hmax indices (Pielou 1966).

$$E = {}^{\mathrm{H}'}/_{H_{max}} \tag{Eq.4}$$

Simpson's diversity (SIP) index was calculated using the formula:

$$D = 1 - \{\textstyle\sum_{ni}(ni - 1)\, N/(N - 1)\} \qquad \text{(Eq.5)}$$

where $n\,i$ n i represents the total number of individuals for each species and N is the total number of individuals for all species (Simpson, 1949). Simpson's index measures the probability that two randomly selected individuals in a sample belong to different species.

Statistical analysis

Pearson correlation tests were conducted using the *corr_coef* function from the R package metan (Olivoto and Lúcio, 2020)**,** to examine the relationships between physicochemical parameters. Seasonal variations in physicochemical measures were assessed using ANOVA tests when the assumptions of normality and homogeneity of residuals were satisfied. In cases where these assumptions were not met, the non-parametric Kruskal-Wallis tests were utilized instead. Afterward, pairwise comparisons were carried out using Tukey's test for ANOVA and pairwise Wilcoxon tests for the Kruskal-Wallis test. Differences in diversity indices between seasons were assessed using generalized linear models (GLMs): with a Poisson distribution for richness, negative binomial distribution for abundance and evenness, and a Gaussian distribution for Shannon, Simpson, and Hmax indices. Additionally, GLMs with Poisson and negative binomial links were used to test for the significant effects of physicochemical parameters on richness and abundance, respectively. The choice of error distribution in GLMs was determined by the characteristics of the dependent variables and the presence of overdispersion (Smith and Warren, 2019). In order to examine shared and exclusive taxa according to season and site, two venn diagrams were generated using the R package '*ggvenn'* (Yan, 2023). The dissimilarity in community assemblages were assessed by a non-metric multidimensional scaling (NMDS) with Bray-Curtis distance using the function '*metaMDS'* from the package vegan (Oksanen et al., 2007). The envfit function was then applied to the NMDS results to fit environmental variables to the NMDS ordination. Moreover, a PERMANOVA test was applied using the function *adonis* implemented in the package vegan (Oksanen et al., 2007) to determine whether community assemblages differed between seasons and sites. Consequently, we performed a pairwise PERMANOVA comparisons using *pairwise.adonis2* function to further explore the differences between groups. All statistical analyses were carried out using R software version 4.2.2 (R Core Team, 2024)**.**

Results

Descriptive analysis of the physicochemical parameters

Table 1 summarizes the physicochemical quality parameters. The mean temperature is 19.38°C, nitrite (NO_2) concentration is 0.29 µmol L^{-1}, and phosphate (PO_4) is 1.06 µmol L^{-1}, with dissolved oxygen levels at 5.67 mg L^{-1}. Nitrate (NO_3) is minimal at 0.16 µmol L^{-1}, while Chl-*a* levels vary widely, averaging 60.20 µg L^{-1}. The pH is nearly neutral at 6.89, and ammonium shows significant fluctuation, averaging 0.83. Suspended solids (SPM) have a mean value of 19.17 µmol L^{-1}.

The Pearson correlation matrix (*Figure 2*) shows strong positive correlations between PO_4 and NH_4 (0.8, $p < 0.001$), and Chl-*a* with both NH_4 (0.9, $p < 0.001$) and PO_4 (0.7, $p < 0.001$). Temperature was moderately positively correlated with Chl-*a* (0.5, $p < 0.05$) and NH_4 (0.4, $p < 0.05$), and negatively correlated with DO (-0.4, $p < 0.05$).

Table 1. *Descriptive analysis of physicochemical water parameters*

Parameter	Mean ± SD	Min	Max
Temperature	19.38 ± 5.11	12.2	26.9
Nitrite (NO_2)	0.29 ± 0.59	0	2.98
Phosphate (PO_4)	1.06 ± 2.00	0	9.924
Dissolved oxygen (DO)	5.67 ± 2.35	2.27	12.55
Nitrate (NO^3)	0.16 ± 0.35	0	1.28
Chl-*a*	60.20 ± 100.36	0	373.8
pH	6.89 ± 0.45	6.32	8.1
Ammonium (NH_4)	0.83 ± 2.34	0	9.924
Suspended particulate matter (SPM)	19.17 ± 16.40	1	76

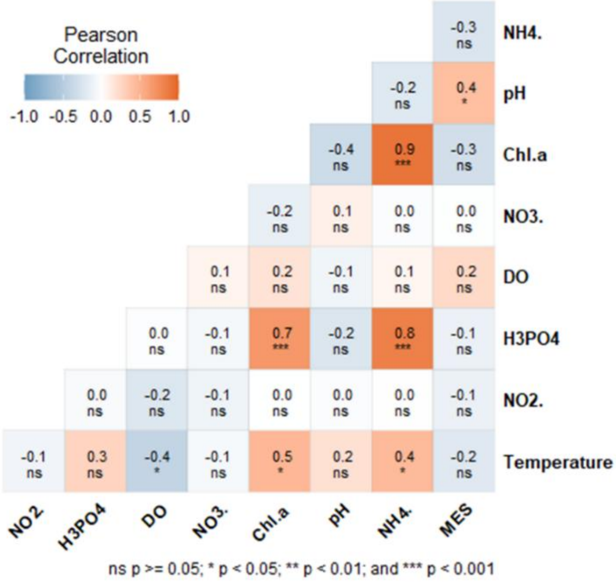

Figure 2. *Heatmap for Pearson correlations between physicochemical parameters*

Seasonal variation in water quality parameters

The ANOVA results show that temperature varies significantly between seasons ($F = 11.67$, $df = 3$, $p < 0.001$), indicating that average temperatures differ across seasons. Pairwise comparisons reveal significant temperature differences between autumn and summer ($p = 0.035$), as well as winter with autumn ($p = 0.038$), spring ($p = 0.018$), and summer ($p < 0.001$). The Kruskal-Wallis test revealed significant seasonal differences for NH_4 ($W = 7.41$, $df = 3$, $p = 0.049$) and dissolved oxygen ($W = 8.49$, $df = 3$, $p = 0.037$). Post hoc comparisons indicated that dissolved oxygen levels differed significantly between winter and spring ($W = 4$, $p = 0.03$), while NH_4 concentrations showed significant differences between summer and winter ($W = 30.1$, $p = 0.028$).

Composition of phytoplankton population of lake Tanga

During this study, the observation of the morphological characteristics of phytoplankton genera collected from Tonga Lake allowed us to identify 43 genera belonging to three classes: Cyanobacteria (12 genera), Diatoms (24 genera), and Dinoflagellates (7 genera). *Figure 3* provides an inventory of these taxa.

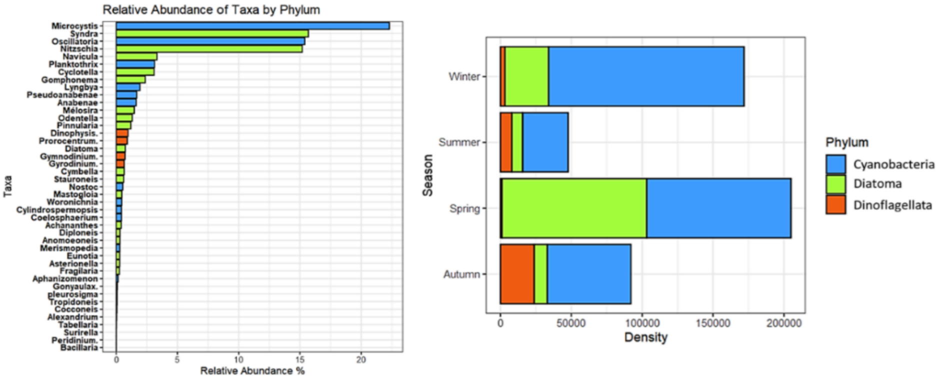

***Figure 3.** Relative abundance of and density of Dinoflagellata, Diatoma and Cyanobacteria taxa*

From a biological perspective, this study demonstrates that the phytoplankton community in Tonga Lake is relatively diverse.

Seasonal trends highlight significant variations in the relative abundance and density of phytoplankton taxa (*Figure 4*). Spring sees prominent peaks in both abundance and density for taxa like Merismopedia and Microcystis, reflecting favorable growth conditions during this period. In contrast, taxa such as Navicula display stable abundance and density throughout the year, indicating their adaptability to varying seasonal conditions.

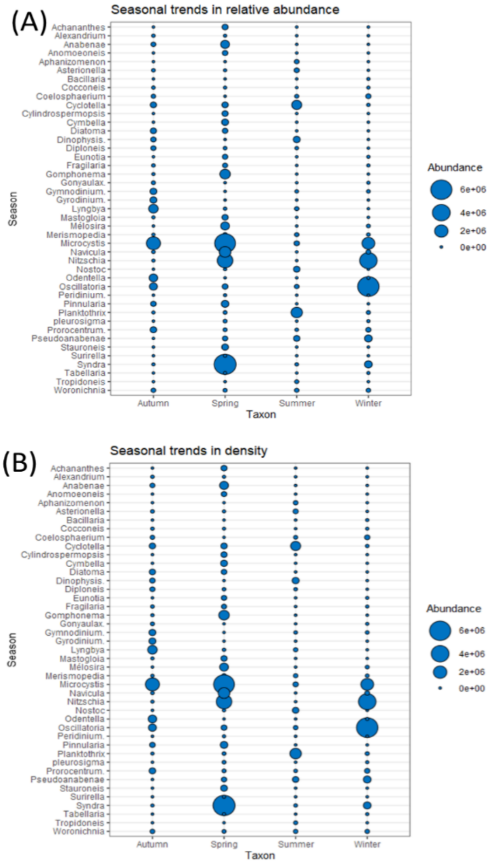

***Figure 4.** Seasonal trends in relative abundance (A) and density (B) of phytoplankton taxa*

Biodiversity metrics exhibit clear seasonal patterns (*Figure 5*), where total abundance peaks in spring with 21,780,002 individuals and drops to 3,649,987 in summer. Likewise, species richness was highest in spring (34 species) and lowest in summer (18 species). The Shannon and Simpson indices registered their highest values in autumn (3.23 and 0.82, respectively) and their lowest in winter (2.05 and 0.67, respectively). Pielou's evenness was highest in summer (0.68), followed by autumn (0.68), spring (0.60), and winter (0.46).

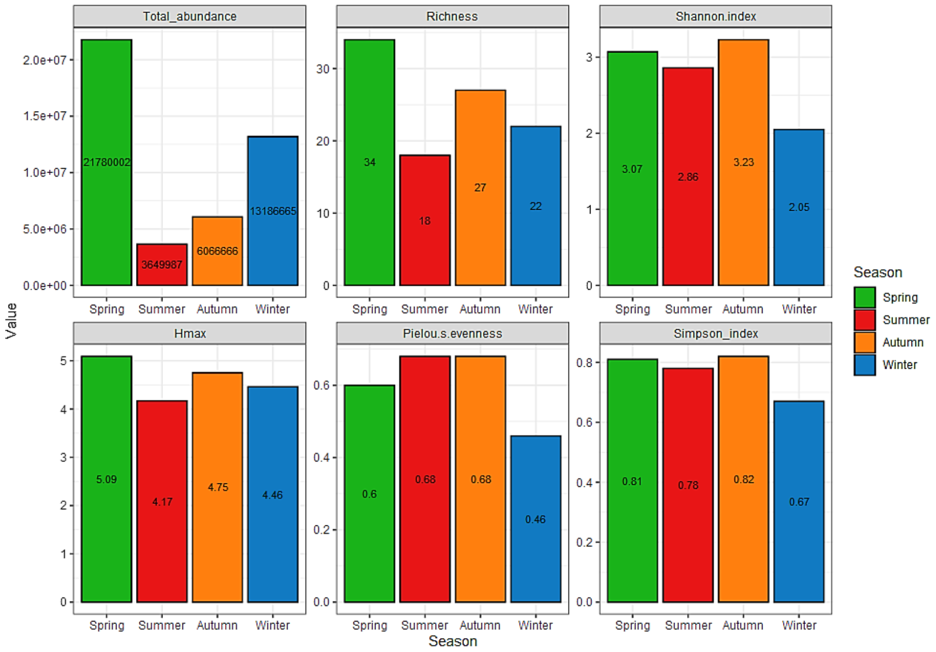

Figure 5. *Barplot illustrating seasonal variation in diversity indices*

The Generalized Linear Model (GLM) revealed a highly significant effect of season on Abundance (F-value = 4.6313, p-value = 0.01288), Richness (F-value = 16.671, p-value = 1.152e-05), and Hmax (F-value = 13.627, p-value = 4.536e-05). Furthermore, the multiple comparison of seasonal differences shows significant differences in abundance (*Figure 6A*). Spring was significantly higher than autumn (estimate = 1.5125, z = 3.042, p = 0.01242); summer had lower abundance compared to spring (estimate = -2.1853, z = -4.396, p < 0.001); and winter exhibited higher abundance compared to summer (estimate = 1.7637, z = 3.548, p = 0.00213). In terms of richness (*Figure 6B*), significant differences were observed where spring had significantly higher richness compared to autumn (estimate = 0.7037, z = 3.946, p < 0.001); summer was significantly lower richness compared to spring (estimate = -1.0275, z = -5.142, p < 0.001); and winter was significantly lower richness compared to spring (estimate = -0.4934, z = -2.961, p = 0.0158).

In addition, significant differences in Hmax were observed, with spring having higher Hmax compared to autumn (estimate = 1.1485, t = 4.583, p < 0.001); summer having lower Hmax compared to spring (estimate = -1.5251, t = -6.085, p < 0.001); and winter having lower Hmax compared to spring (estimate = -0.7214, t = -2.878, p = 0.004).

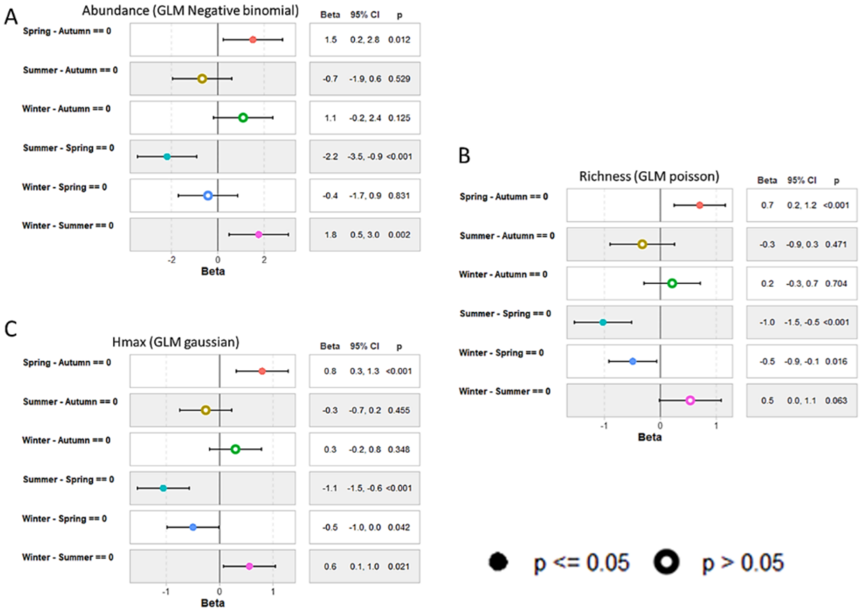

***Figure 6.** Forest plot showing pairwise comparison of season based on generalized linear models (GLMs) results*

The model shows that both temperature (Estimate: -0.054, z = -3.295, p < 0.001) and dissolved oxygen (Estimate: -0.123, z = -3.303, p < 0.001) have significant negative effects on species richness (*Figure 7 AB*). Similarly, temperature (Estimate: -0.138, z = -3.245, p = 0.001) and dissolved oxygen (Estimate: -0.190, z = -2.090, p = 0.037) also have significant negative effects on total abundance (*Figure 7 CD*).

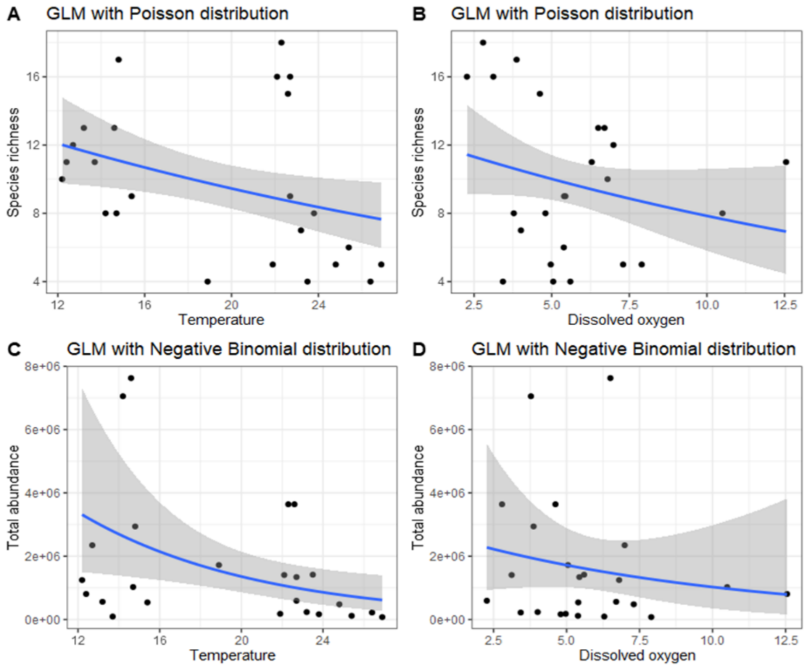

***Figure 7.** Generalized linear model (GLM) illustrating the effects of temperature and dissolved oxygen on species richness (A-B) with a Poisson distribution and total abundance (C-D) with a negative binomial distribution. Shading indicates the 95% confidence intervals for the mean*

DOI: http://dx.doi.org/10.15666/aeer/2303_39393956

The two stations shared 37 taxa, accounting for 79.1% of the total richness. Station 1 had 7 exclusive taxa: *Bacillaria sp, Odontella sp, Pleurosigma sp, Asterionella sp, Surirella sp, Tropidoneis sp*, and *Peridinium sp*. Conversely, Station 2 had only two exclusive taxa: *Cylindrospermopsis sp*. and *Aphanizomenon sp* (*Figure 8A*). The four seasons shared 8 common taxa, accounting for 18.6% of the total richness (*Figure 8B*). Spring had the highest number of exclusive taxa (7), followed by summer with 2 unique taxa (*Aphanizomenon sp*, *Tropidoneis sp*), and only 1 unique taxa for both winter (*Bacillaria sp*) and autumn (*Gyrodinium sp*). Additionally, spring shared 6 and 4 exclusive taxa with autumn and winter respectively, while autumn and winter shared 2 exclusive taxa namely *Gonyaulax sp*, and *Odentella sp*.

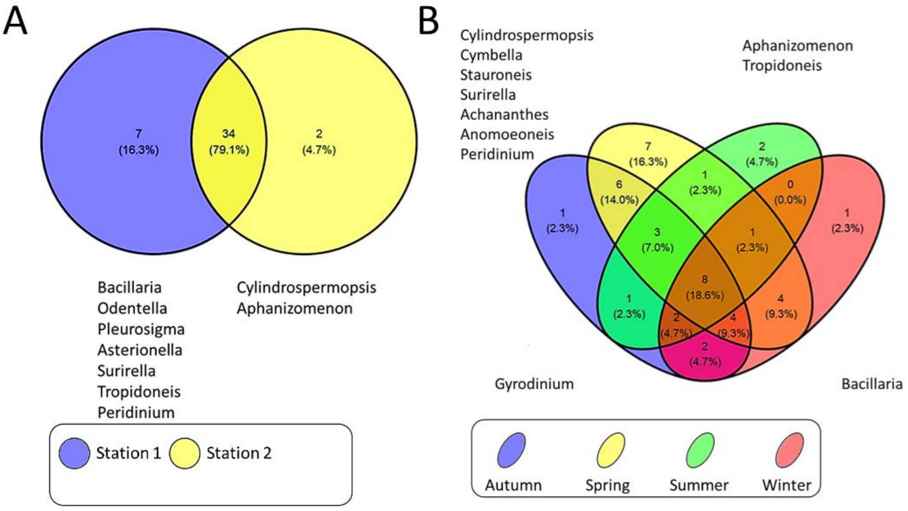

Figure 8. *Venn diagrams displaying exclusive and shared taxa among sampling stations (A) and across seasons (B)*

The NMDS plot illustrates seasonal variations in the assemblage of Dinoflagellates, Diatoma, and Cyanobacteria taxa (*Figure 8*). Summer was characterized by *Aphanizomenon sp*, *Nostoc sp*, *Asterionella sp*, *Planktothrix sp*, *Dinophysis sp*, *Cyclotella sp*, and *Tropidoneis sp*, along with high levels of NH_4, Chl-*a*, and temperature. In contrast, spring was characterized by taxa including *Stauroneis*, *Achnanthes*, *Cymbella*, *Anomoeneis*, *Gomphonema*, *Mastogloia*, *Navicula*, *Nitzschia*, *Peridinium*, *Surirella* and elevated nitrite levels. Additionally, Diatoma sp, Gyrodinium sp, Diploneis, Pinnularia, and Lyngbya sp were abundant in autumn. This observed seasonal pattern was supported by the PERMANOVA test, which revealed a significant effect of season on community composition (F= 2.9769, p-value = 0.001). In contrast, sites did not significantly affect community composition (F= 1.2013, p-value = 0.257).

The pairwise comparisons reveal significant differences in community composition between summer and the three other seasons: spring (F = 4.8541, p-value = 0.003), autumn (F = 2.112, p-value = 0.006), and winter (F = 4.04, p-value = 0.005). Additionally, spring was significantly different from both autumn (F = 2.7588, p-value = 0.004) and winter (F = 2.4712, p-value = 0.014). However, autumn and winter are not significantly different in terms of composition (F = 1.8242, p-value = 0.07). The NMDS plot depicts the seasonal variations in the assemblages of Dinoflagellates, Diatoms, and Cyanobacteria taxa (*Figure 9*). During the summer, the assemblage was dominated by

Aphanizomenon sp., *Nostoc sp.*, *Asterionella sp.*, *Planktothrix sp.*, *Dinophysis sp.*, *Cyclotella sp.*, and *Tropidoneis sp.*, coinciding with elevated levels of NH_4, Chl-*a*, and temperature. In contrast, spring was characterized by taxa such as *Stauroneis*, *Achnanthes*, *Cymbella*, *Anomoeneis*, *Gomphonema*, *Mastogloia*, *Navicula*, *Nitzschia*, *Peridinium, and Surirella, along with increased nitrite concentrations. Furthermore, Diatoms sp., Gyrodinium sp., Diploneis*, *Pinnularia, and Lyngbya sp*. were notably abundant in the autumn season.

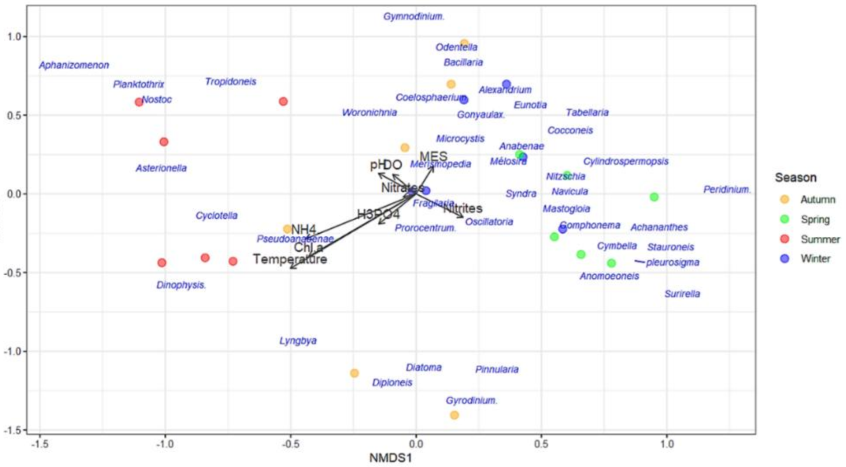

Figure 9. *Non-metric multidimensional scaling (NMDS) based on the Bray-Curtis dissimilarity index, showing seasonal variation in phytoplankton community composition, and physicochemical parameters*

Discussion

The objective of this study is to characterize the phytoplankton communities within Tonga Lake, specifically by examining their taxonomic composition, dynamics, and the interactions with environmental factors. Lakes serve as intricate ecosystems that support a wide variety of flora and fauna. They play a pivotal role in the hydrological cycle and contribute to the regulation of local climatic conditions (Prakash, 2021; Kumar et al., 2024).

Despite their fundamental ecological functions, lakes are severely threatened by anthropogenic pollution, climate change, and the introduction of invasive species, which jeopardize biodiversity and the overall health of these ecosystems (Bănăduc et al., 2022). Abiotic factors create the necessary physical and chemical conditions conducive to the growth and sustainability of phytoplankton populations (Etisa et al., 2024).

Temperature is a significant determinant of the growth, reproduction, and survival of aquatic organisms (Aminot and Chaussepied, 1983). It directly influences critical water quality parameters, such as dissolved oxygen and nutrient availability. Microalgae, for example, display optimal growth rates within a temperature range of 15 to 26°C, although certain species demonstrate tolerance to extreme temperatures (Kumar et al., 2010). This finding aligns with the data reported by Draredja et al. (2019) for Mellah Lagoon and is consistent with observations from other Mediterranean lagoons (*Table 2*). Elevated temperatures can enhance enzymatic activity, thereby stimulating phytoplankton photosynthesis and growth (Doney, 2006).

Table 2. *Summary of the physicochemical state of several Mediterranean lakes and lagoons*

Water body	T	DIN	SRP	Chl-*a*	References
Biguglia (F)	9–27.5	0.7–77.1	–	–	(Vanina et al. 2006)
Urbino (F)	6–31	0.2–5.5	–	–	(Vanina et al. 2006)
Thau (F)	4–27	20.7–136.1	0.1–20.9	1.1–14.1	(Vincent et al. 2006)
Gialova (G)	10.7–29.7	0.08–44.5	0.01–0.2	0.08–11.7	(Petihakis et al. 1999)
Logarou (G)	13–24	0–8.7	0.12–1	1.8–20.9	(Kormas et al. 2001)
Tsoukalio–Rodia (G)	11.3–28.3	0–9.3	0–0.1	0.2–6.5	(Kormas et al. 2001)
Orbetello (I)	6–28	12–85.1	0.1–0.9	–	(Lenzi et al. 2003)
Venice (I)	4.8–32	2–41.5	0.3–2.9	0.2–29.1	(Sfriso 1995)
Cabras (I)	6.6–29.3	2.86–16	0.2–4	4–197	(Pulina et al. 2012)
Mar Menor (S)	10.2–30.7	1.5–8.9	0–0.6	0.7–5.6	(Lloret et al. 2008)
Ghar El Melh (T)	11–26.9	2.9–7	0.06–0.3	–	(Dhib et al. 2016)
El Mellah Lagoon (A)	12.2–28.8	0.3–8	0.02–1.7	0.08–5.5	(Draredja et al. 2019)
Tonga Lake	12.2-26.9	0-14.18	0-9.92	0-374	The current study
The average in the Mediterranean	8.73-28.6	3.4-37.3	0.09-3.26	1.02-32.26	

The surface water pH levels in Tonga Lake fluctuated between 6.5 and 9.0 (JORA, 2011). The pH value recorded for Tonga Lake was 6.89, which falls within the World Health Organization (WHO) standards (6.5-8.5) (World Health Organization, 2017), and is comparable to those reported by Bensafia (2005), and Loucif et al. (2020) for the same lake. The neutral to slightly alkaline pH levels are optimal for aquaculture development, supporting the sustainability of fish populations (Rodier et al., 2009).

Dissolved oxygen is crucial for ecosystem stability (Haritash et al., 2016; Lv et al., 2024). Its concentration is influenced by various parameters, including temperature, salinity, and biogeochemical nutrient cycles (Mavropoulou et al., 2020; Sundararaman and Shanmugam, 2024). The average dissolved oxygen level measured is approximately 5.70 mg L^{-1}, which is within the acceptable range established by the WHO (5-8 mg L^{-1}) (World Health Organization, 2017). Elevated levels of dissolved oxygen in aquatic systems generally indicate a healthy environmental status (Langendorf et al., 2021). This finding stands in contrast to findings reported by Loucif et al. (2020), which indicated a state of eutrophication characterized by significantly lower oxygen levels in the same region.

The evaluation of the lake's ecological status is based on the concentrations of nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), and phosphate (PO_4). In this study, the average concentration of NO_3 was found to be 0.16 µmol L^{-1}, a value that is significantly lower than the levels recommended by the World Health Organization (2017) and Rodier et al. (2009) suggest that normal levels of NO_3 range between 142 to 214 µmol L^{-1}.

Table 2 presents the primary physical and chemical parameters of various Mediterranean inland and coastal water bodies. The parameters include temperature (T, °C), dissolved inorganic nitrogen (DIN, µmol L^{-1}), soluble reactive phosphorus (SRP, µmol L^{-1}), and Chl-*a* (µg L^{-1}). The locations are denoted as follows: Algeria, France, Greece, Italy, Spain, and for Tunisia.

Similarly, the mean concentration of NH_4 in Tonga Lake was 0.80 µmol L^{-1}, which is considerably lower than the reference values established by the WHO (2017) and reported by Loucif et al. (2020). Additionally, the phosphate (PO_4) concentration in the lake was measured at 1.06 µmol L^{-1}, which does not exceed the threshold recommended by Rodier et al. (2009) and WHO (2017). The mean nutrient concentrations for NO_3, NO_2, NH_4, and PO_4 in this study remain substantially lower than those documented by Loucif et al. (2020) and Naili et al. (2021) in Tonga Lake, as well as by Messerer et al. (2019) in Oubeira Lake.

Suspended particulate matter (SPM) was identified as the primary factor contributing to water turbidity, with an average concentration of 19.70 mg L^{-1}, which falls within the acceptable limits set forth by ANRH (2021) (0-30 mg L^{-1}), indicative of good water quality. According to Benyacoub et al. (2011), low SPM concentrations correlate with reduced phytoplankton proliferation and insufficient favorable environmental conditions. Amira and Bougdah (2018) noted that SPM concentrations exhibited significant seasonal variability, influenced by precipitation events and water discharge.

The average concentration of Chl-*a* in Tonga Lake is approximately 60 µg L^{-1}. This concentration is among the highest recorded in the Mediterranean inland and coastal water bodies (*Table 2*). In Tonga lake, phytoplankton species are categorized into 43 genera across three classes: Cyanobacteria (12 genera), Diatoms (24 genera), and Dinoflagellates (7 genera). The predominance of diatoms has also been noted by Draredja et al. (2019) in Mellah lagoon, where 53 species were identified.

The prevalence of diatoms in this lake may be attributed to their ability to directly assimilate nutrients from the water-sediment interface (Bonin, 1988; Draredja et al., 2019). The competitive interactions among phytoplankton species across different algal groups depend on the extent of vertical mixing. Heavier diatoms typically gain a competitive edge during periods of vigorous mixing, while more buoyant phytoplankton, such as cyanobacteria, and tend to dominate under thermally stable conditions (Huisman et al., 2004).

Total abundance and species richness peak in spring and decline in summer, likely due to favorable environmental conditions and nutrient availability (Winder and Sommer, 2012). Station 1 is characterized by the dominance of diatom species such as *Bacillaria sp., Odontella sp., Pleurosigma sp., Asterionella sp., Surirella sp., Tropidoneis sp., and Peridinium sp.,* which may be related to the specific location of this station. In contrast, Station 2 is characterized by only two exclusive taxa: *Cylindrospermopsis sp*. and *Aphanizomenon sp*., both of which are species of toxic cyanobacteria typically found in disturbed sites.

The analysis of the phytoplankton community and seasonal variations revealed that the four seasons shared eight common phytoplankton taxa, representing 18.6% of the total richness. Spring exhibited the highest number of exclusive taxa, followed by summer, while autumn and winter showed fewer unique taxa.

Conclusion

This study evaluated the physicochemical and biological attributes of Tonga Lake, which is labeled as a Ramsar site. A total of 43 phytoplankton genera were identified, with diatoms being the most abundant with 24 genera, followed by 12 genera of Cyanobacteria and 7 genera of Dinoflagellates. The findings underscore the seasonal variations within these taxonomic groups. During the summer season, the phytoplankton community was predominantly characterized by genera such as *Aphanizomenon, Nostoc, Asterionella, Planktothrix, Dinophysis, Cyclotella, and Tropidoneis*, in conjunction with increased levels of ammonium (NH4), Chl-*a*, and temperature (T°). In contrast, spring saw a higher prevalence of genera including *Stauroneis*, *Achnanthes*, *Cymbella*, *Anomoeneis, Gomphonema, Mastogloia, Navicula, Nitzschia, Peridinium, and Surirella*. Furthermore, autumn was notable for a significant presence of *Diatoms, Gyrodinium, Diploneis, Pinnularia, and Lyngbya sp.*

Funding. The research was not financially supported by any particular grant or funding organization, whether governmental, commercial, or nonprofit.

Availability of data and materials. The data and materials used in this study are available upon request.

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