Assessment of the phytoplankton diversity and its temporal dynamics in the freshwater ecosystem of the Beni-Zid dam, Algeria

Maya Ghannam[1,3,*], Zine Eddine Boudjellab[1,3], Ennaghra Nadjet[3,5], Nadjla Chaib[1,4], Zohra Chekroud[2,3], Boulehsa Asma[2,3], Boudeffa Khaled[3], Abdelkader Basli[2,3]

[1] Laboratoire de Catalyse, de Bioprocédés et Environnement (LCBE), University of 20 August1955, B.P.26 road : El-Hadaiek Skikda 21000. Algeria.

[2] Research laboratory of Interactions, Biodiversity, Ecosystems and Biotechnology, University of 20 August1955, B.P.26 road : El-Hadaiek Skikda 21000. Algeria.

[3] Department of Natural and Life Sciences, Faculty of Sciences, University of 20 August1955, B.P.26 road : El-Hadaiek Skikda 21000. Algeria.

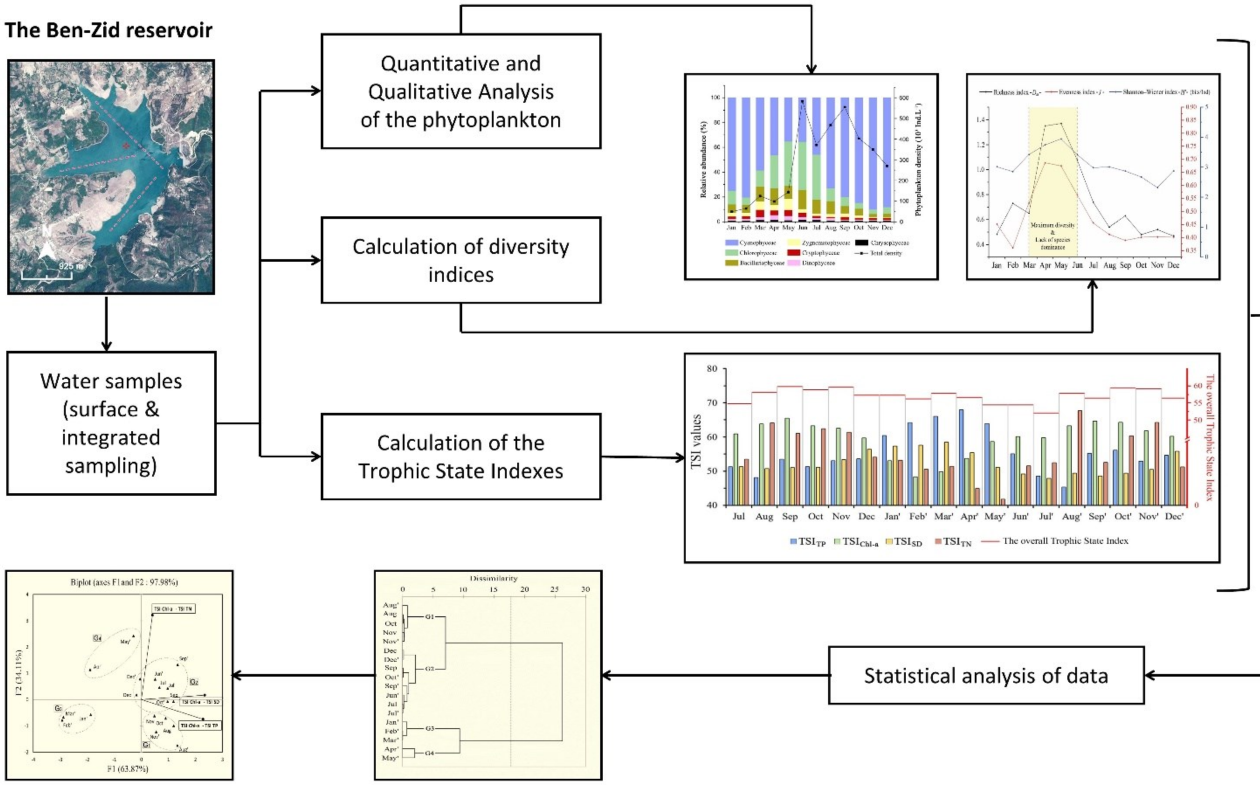
[4] Department of Process Engineering, Faculty of Technology, University of 20 August1955, B.P.26 road : El-Hadaiek Skikda 21000. Algeria.

[5] Laboratory of Biochemistry and Environmental Toxicology, University of Badji Mokhtar, Annaba 23000, Algeria.

Corresponding author :

Maya Ghannam, Tel: +213-0674973580. Email : mayaghannem@gmail.com

GRAPHICAL ABSTRACT



ABSTRACT

The temporal variability of diversity and cell abundance of the phytoplankton community was studied in the Beni-Zid reservoir using the Utermöhl method. A total of 54 taxa were identified, belonging to seven classes: Chlorophyceae (17 taxa), Bacillariophyceae (15 taxa), Cyanophyceae (14 taxa), Zygnematophyceae (4 taxa) Cryptophyceae (2 taxa), Dinophyceae (1 taxon), and Chrysophyceae (1 taxon). Throughout the study period, perennial species were *Oscillatoria limnetica*, *Microcystis aeruginosa*, *Pinnularia major* and *Dinobryon sp.* The highest cell densities were 585.10^4 Ind.l^{-1} recorded during June, with quantitative dominance of Cyanophyceae. The highest diversity and a quasi-homogeneous distribution of cells enumerated on the different inventoried classes were observed during the period from March to June; this is indicated by the maximum values of the evenness index of Pielou (*J*) and the Margalef index (D_m). The monthly assessment of the water trophic level by calculating the trophic state index (TSI), indicates an eutrophic state of the dam water. It confirms the tendency for blue-green algae to dominate the existing phytoplankton community. The Hierarchical Cluster Analysis (HCA) and the principal components analysis (PCA) both applied to the data of deviations calculated between the different TSIs, showed a strong correlation between the reduction of water transparency by planktonic microalgae cells and the limitation of its growth by the phosphorus element, this particularly concerns the period of the year from August to November. While nitrogen element limitation hardly occurred at any time of the year.

Keywords: Beni-Zid reservoir, Diversity index, *Microcystis aeruginosa*, Trophic state index.

1. Introduction

In Algeria, the economic development has increased over the last 40 years. This development has involved greater land use, increased population urbanization, expansion of irrigated agriculture and industrialization. These factors greatly influence the water supply, both quantitatively and qualitatively. Knowing the current state of the waters and determining the factors and mechanisms affecting their quality are prerequisites for drawing up a global management plan, to preserve this resource.

Water dam biological monitoring is critical for checking water quality and maintaining its suitability for various purposes, including water treatment (Bawa *et al.* 2019). Evaluating microbial indicators, such as total and fecal coliforms, has been a common practice in this context. However, it's worth noting that certain vital aspects of water quality assessment often go overlooked. One such parameter is the proliferation of phytoplankton, which is comparably significant to fecal pollution, yet frequently disregarded in monitoring efforts (Bellinger and Sigee, 2015).

In addition, as a diverse group of microorganisms, phytoplankton substantially influences on the aquatic ecosystem. Their population density can significantly impact water treatment processes, particularly water purification (Czyżewska and Piontek, 2019). A high density of phytoplankton can pose difficulties across different stages of the treatment process, affecting the overall quality of the treated water. Therefore, expanding the monitoring activities' scope is imperative to encompass qualitative and quantitative data collection from the algal compartment.

Microalgae have been extensively recognised as valuable bioindicators in aquatic environments, owing to their diverse role (Fakioglu, 2013; Soeprobowati, 2016; Heramza *et al.* 2021). These organisms exhibit a remarkable sensitivity to environmental changes, often responding to alterations in their surroundings by adjusting their community structure. This sensitivity makes microalgae an effective tool for detecting and reflecting the presence of various chemicals and pollutants in water bodies (Ansari and Gill, 2014; Skála, 2015; Sharma and Singh, 2016; Paulino *et al.* 2018; Bazarova *et al.* 2019; Prasertsin *et al.* 2021; Jose and Xavier, 2022). As a result, analysing changes in the composition and abundance of microalgae can provide insight into potential water resource contamination (Wan Maznah and Makhlough, 2014; Wagner *et al.* 2016; Kostryukova *et al.* 2021). The importance of monitoring microalgae becomes particularly evident when considering the contribution of nutrient pollutants, such as excessive nutrients like nitrogen and phosphorus, to water quality deterioration. Nutrient enrichment can lead to eutrophication, a phenomenon characterized by an overgrowth of algae and subsequent depletion of oxygen levels in the water (Karydis, 2009; Mishra, 2023). This process severely affect aquatic ecosystems, disrupting biodiversity and impairing essential ecosystem functions (Paerl, 2017; Rahayu and Nugroho, 2020).

Moreover, the monitoring of phytoplankton extends beyond assessing water quality alone. It also valuates potentially toxigenic species proliferation within the phytoplankton community. The presence of these species can have far-reaching implications for the aquatic ecosystem and the surrounding biodiversity.

Disruption of ecosystem functions and alteration of species composition can result from the unchecked growth of harmful phytoplankton species. Therefore, a comprehensive understanding of the phytoplankton dynamics is crucial for maintaining a balanced and healthy aquatic environment (Wood *et al*. 2016; Djabourabi *et al.* 2017).

Based on the socio-economic importance of water resources and the various challenges affecting their quality, our study focused on the phytoplankton community of the Beni-Zid water dam, one of the largest dams in northeastern Algeria. The Beni-Zid water dam, a critical resource in northeastern Algeria, plays a key role in meeting agricultural, industrial, and domestic water needs. However, its water quality is increasingly threatened by various anthropogenic pressures, including nutrient enrichment and potential eutrophication. To our knowledge, no similar study has been previously conducted on this dam.

The main objectives of our work are as follows:
1-Establishing a comprehensive inventory of phytoplankton species: This includes identifying all taxa present in the dam, with particular emphasis on potentially toxigenic species that could pose ecological and public health risks; 2-Studying the seasonal dynamics and succession patterns of phytoplankton: Investigating the temporal changes in species composition and the dominant phytoplankton classes over the different seasons, aiming to understand the ecological drivers behind these shifts; 3-Monitoring the trophic state of the dam on a monthly basis: Assessing how nutrient levels and other environmental factors influence the dam's water quality, as well as its susceptibility to eutrophication; 4-Evaluating the role of phytoplankton as bioindicators: By analyzing the sensitivity of specific phytoplankton groups to environmental changes, 5-Identifying potential risks associated with harmful algal blooms: This involves monitoring the proliferation of phytoplankton species that may produce toxins; 6-Contributing to

sustainable water resource management: By generating baseline data on the phytoplankton community and water quality.

Despite the fact that this study is geographically limited to a single water dam, and its temporal scope, covering only one year of monitoring, may restrict the generalizability of the findings to other water bodies, the research provides valuable insights into the phytoplankton dynamics of this specific ecosystem. It also offers a comprehensive and integrated view of the phytoplankton community's structure, thereby supporting the conservation and management of this critical water resource.

2. Materials and methods

2.1. Study area

Beni-Zid water dam was built on the Ben-Zid wadi, part of the Wadi Guebli basin. It is located in the northeast of Algeria (Fig.1), 20 km south of Collo city, 90 km from the city of Skikda, and 120 km from Constantine. This region is characterized by a semi-arid Mediterranean climate, including a medium to high water load (November-April), followed by another period with rare rainfall to none. The reservoir is intended for the Collo, Beni Zid, Kerkera, and Cheraia Cities drinking water supply (in total: 85,000 inhabitants), and irrigation of all Beni-Zid and Guebli valleys. The main features of the basin and the reservoir are shown in Table 1.

Table 1. Main characteristics of the Beni-zid reservoir.

Characteristics	**Measurements**
Mean altitude (m)	354
Annual mean water inputs (millions of m^3)	28.5
Surface area (ha)	286.3
Total water capacity (millions m^3)	40

Regulated water volume (millions m^3)	19.9
Dikelenght (m)	150
DikeHeight (m)	53
Watershed Area (Km^2)	58.5
Maximal length (Km)	3.89
Mean width (m)	625
Mean depth (m)	10.3
Hydraulic residence time (days)	11

2.2. Collection and treatment of samples

Samples were collected monthly from January to December 2022 for qualitative and quantitative phytoplankton analyses. These samples were recovered by horizontal tows taken at 1 m depth, in line at very low-speed line, along transects covering all parts of the dam and using a phytoplankton net with a mesh size of 30 µm.

Figure 1. Geographical location of the Ben-Zid reservoir and sampling station.

To ensure an accurate investigation of the smaller phytoplankton species (< 30 µm), which were discarded in net samples, integrated water column samples were collected by a hose-sampler accommodated to cover the whole euphotic zone profundity, measured by the Secchi disk (Coté et al. 2002). This sampling was made from the area where the dam's deepest point is located at 36°54'43"N ; 6°29'45"E (Fig. 1). Water samples were fixed immediately with Lugol's solution (1% v/v) and then stored in a dark and cool place until analysis (Côté *et al.* 2005).

2.3. Quantitative and Qualitative Analysis of the phytoplankton

The density of phytoplankton cells was assessed in fixed subsamples and placed in 5 ml chambers for over 8 hours, following the method described by Uthermöhl (1958) (Utermöhl, 1958), and were later examined using an Olympus CKX31 inverted microscope. Species were counted on random fields until 400 counting units (single cell, colony, or filament) were recorded, ensuring an accuracy of 95%.

The Identification was done with specific literature and was conducted to the lowest possible taxonomic level (species, genus), and classified into major taxonomic groups: Chlorophyceae, Xanthophyceae, Cyanobacteria, Chrysophyceae, Cryptophyceae, Bacillariophyceae, Zygnemaphyceae and Euglenophyceae. According to Komárek and Anagnostidis (2005) (komárek and Anagnostidis, 2005) and Round et al. (2007) (Round *et al.* 2007) the cellular criteria used for the identification of phytoplankton are: the thallus organization (filamentous, colonial, isolated cells), its shape (spherical, cubical, amorphous, regular, elongated, reticulated, straight, spiraled); the presence or absence of flagella and their number; types of cells (vegetative cells, heterocysts, akinetes), and their shape (spherical, cylindrical, ellipsoidal...); the presence of mucilage and its characteristics (color, visibility, sharp or diffuse boundaries, lamellae, homogeneity) ; Cell dimensions and their contents (gas vacuoles, granules). Species names were checked for validity against Algae Base (Guiry and Guiry, 1996).

2.4. Calculation of diversity indices

The description of the species richness of the environment studied was established using an univariate analysis approach through the diversity index. The indices were: the Margalef (1967) richness index (Margalef, 1967), shown in Eq. (1), the Shannon–Wiener index (Shannon and Weaver, 1963), shown in Eq. (2) and the Pielou (1966) evenness index (Pielou, 1966), shown in Eq. (3).

$D_m = (S-1)/\ln N$ **Eq. 1**

$H' = -\sum_{i=1}^{S} pi \ln pi$ **Eq. 2**

$J = H' / \ln S$ **Eq. 3**

Where pi = ni/N ; ni= the number of individual species within a given sample; N= the total number of individuals of all species within a given sample; S=the number of species within a given sample.

2.5. Calculation of the Trophic State Indexes

Trophic state of the dam's studied water was assessed monthly from July 2021 to December 2022. It was carried out based on the calculation of the trophic state index (TSI) using a logarithmic transformation (Equation 5, 6, 7 and 8) of the mean values of four variables, namely: the concentrations of chlorophyll a (Chl-a) were measured after water samples filtration through membrane filters (45 mm diameter, Whatman GF/CTM, Germany), pigments were extracted using 70% aqueous acetone and measured by spectrophotometry (UV-Visible Jenway 6305) according to Equation (4):

$$\text{Chl-a } (\mu g.L^{-1}) = [(A_0 665 - A_0 750) - (A_a 665 - A_a 750)] \quad \text{Eq. 4}$$

where, $A_0\lambda$ represents the absorbances before acidification, while $A_a\lambda$ represents the absorbances after acidification by adding a few drops of 1 N hydrochloric acid. The variables v, V, and l refer to the volume (in mL) of acetone used, the volume (in L) of the filtered sample, and the length of the optical path of the measuring cell (l = 1 cm), respectively [30].

The other parameters used to calculate the TSI are : Secchi depth (SD); total phosphorus (TP) using spectrophotometer method after digestion with persulfate; and finally, the total nitrogen (TN) calculated by the sum of the three forms of nitrogen concentrations: nitrate (NO_3-N) and nitrite (NO_2-N) analysis using sulfosalicylic acid and Zambelli reaction methods, and Kjeldahl nitrogen (KN) using oxidative mineralization with peroxodisulfate methods. All of the methods used for measuring pigmentation and nutrients in water are described in Rodier (2009) (Rodier and 2009). The equations are as follows:

$TSI_{TP} = 14{,}42 \ln(TP) + 4{,}15$ **Eq. 5** (Carlson, 1977)

$TSI_{SD} = 60 - 14{,}42 \ln(SD)$ **Eq. 6** (Carlson, 1977)

$TSI_{Chl\text{-}a} = 9{,}81 \ln(Chl\text{-}a) + 30{,}6$ **Eq. 7** (Carlson, 1977)

$TSI_{TN} = 54{,}45 + 14{,}43 \ln(TN)$ **Eq. 8** (Kratzer and Brezonik, 1981)

The values of the various TSIs calculated, are then compared with the limit values determining the different levels of trophic status of naturals surface waters (table 2).

Table 2. System for assessing the trophic status of a water body (Carlson and Simpson, 1996).

Value of TSI	Conditions
< 30	**Oligotrophy:** Clear water, oxygen throughout the year in the hypolimnion.
30 – 40	Hypolimnia of shallower lakes may become anoxic.
40 – 50	**Mesotrophy:** Water moderately clear; increasing probability of hypolimnetic anoxia during summer.
50 – 60	**Eutrophy:** Anoxic hypolimnia, macrophyte problems are possible.
60 – 70	Blue-green algae dominate, algal scums and macrophyte problems.
70 – 80	**Hypereutrophy:** (light limited productivity). Dense algae and macrophytes.
> 80	Algal scums, few macrophytes.

The interrelationships between the calculated values of the different TSIs, provides additional information about the factors prevailing on the water surface. The meaning of the comparison results between the various TSIs, the deviation, is summarized in Table 3.

Table 3. Meaning of the interrelationships between TSIs values (Carlson and Simpson, 1996).

Relationship Between TSI Variables	**Conditions**
$TSI_{Chl\text{-}a} = TSI_{TP} = TSI_{SD}$	Algae dominate light attenuation; TN/TP ~ 33:1
$TSI_{Chl\text{-}a} > TSI_{SD}$	Large particulates, such as *Aphanizomenon* flakes, dominate
$TSI_{TP} = TSI_{SD} > TSI_{Chl\text{-}a}$	Non-algal particulates or color dominate light attenuation
$TSI_{SD} = TSI_{Chl\text{-}a} > TSI_{TP}$	Phosphorus limits algal biomass (TN/TP > 33:1)
$TSI_{TP} > TSI_{Chl\text{-}a} = TSI_{SD}$	Algae dominate light attenuation but factors such as nitrogen limitation, zooplankton grazing or toxics limit algal biomass.

2.6. Statistical analysis of data

In order to compare the cell density obtained for each season of the year 2022, a one way anova was realized using the XLSTAT 2023.1.6 software. Also, to highlight periods of the year when biotic and abiotic conditions in the freshwater ecosystem are similar, a Hierarchical Cluster Analysis (HCA) was performed. This involved calculating the percentage of similarity (or conversely, dissimilarity) between months of the year based on deviations in different TSIs ($TSI_{Chl\text{-}a}$, TSI_{SD}, TSI_{TP}, and TSI_{TN}). Additionally, a Principal Components Analysis (PCA) was conducted to determine the type of deviation that characterizes each group of months and to assess the degree of correlation between these different deviations. These statistical analyses were carried out using SPSS Statistics 27.0, set under varimax rotation. Additionally, to facilitate the discussion of certain results, the months of the year have been conventionally grouped into seasons as follows: autumn (September, October, and November), winter (December, January, and February), spring (March, April, and May), and summer (June, July, and August).

3. Results and discussion

3.1. Phytoplankton diversity and population density

The common phytoplankton species recorded during the study period and their average cell density are presented in Table 4. A total number of 54 species were identified, belonging to seven different classes, Chlorophyceae (31%), Bacillariophyceae (27%), Cyanophyceae (26%), Zygnematophyceae (7%) Cryptophyceae (4%), Dinophyceae (2%) and Chrysophyceae (2%).

Among the 54 identified species, 8 are described as perennial because they are observed in water samples throughout the study period, of which Bacillariophyceae constitutes one-third of these perennial species. On the contrary, other species are detected only for not exceeding two months, usually corresponding to April and May in which, water samples were characterized by the highest species richness (The count of different species within a sample), compared to the rest of 2022 months. While quantitatively, eight out of 54 species exceeded a monthly average cell density of 10^4 Ind.L^{-1}, half of them belong to the Cyanophyceae (*Oscillatoria limnetica, Trichodesmium sp., Pseudanabaenasp., Anabaena sp.*)

Table 4. Phytoplankton diversity, abundance, and seasonality in Beni-Zid reservoir **W**: Winter, **A**: Autumn, **Sg**: spring, **S**: Summer), **P**: Perennial, **(+)**:< 100 Ind.L^{-1}; **(++)**:101-1000 Ind.L^{-1}; **(+++)**: 1001-10000 Ind.L^{-1}; **(++++)**: > 10^4Ind.L^{-1}.

Taxa	**Average cell density**	**Seasonality**
Cyanophyceae		
Aphanocapsa sp. (Nägeli ex Kützing) Nägeli	+	Sg
Oscillatoria limnetica Lemmermann	++++	S-A-W
Microcystis flosaquae (Wittrock) Kirchner	+	S-A
Nodularia sp. Mertens ex Bornet&Flahault	++	S-A
Chroococcus limneticus Lemmermann	++	Sg
Gloeocapsa sp. Kützing	++	Sg
Merismopedia sp. Men	++	Sg-S-A

Trichodesmium sp. Ehrenberg ex Gomont	++++	W-Sg
Microcystis aeruginosa Kützing	+++	P
Pseudanabaena sp. Lauterborn	++++	W-S-A
Chrocococcus sp. Nageli	++	S-A
Lyngbya sp. C. Agardh ex Gomont	+++	P
Oscillatoria margaritifera Kützing ex Gomont	++	W-Sg-S
Anabaena sp. Bory ex Bornet&Flahault	++++	W-A
Chlorophyceae		
Botryococcus sp. Kützing	++	W-Sg-A
Closteriopsis acicularis (Chodat) J.H.Belcher&Swale	+	W-Sg
Coelastrum microporum Nägeli	++	W-Sg
Scenedesmus acuminatus (Lagerheim) Chodat	+++	Sg
Oocystis marssonii Lemmermann	++	Sg-A
Scenedes musellipticus Corda	+++	W-Sg
Monoraphidium griffithii (Berkeley) Komárková-Legnerová	+	Sg-A
Scenedesmus acuminatus (Lagerheim) Chodat	++	W
Crucigenia tetrapedia (Kirchner) Kuntze	+	Sg
Oocystis lacustris Chodat	++	W-Sg
Chlamydomonas sp. Ehrenberg	+	W
Kirchneriella lunaris (Kirchner) Möbius	+	Sg-A
Tetraëdron caudatum (Corda) Hansgirg	++	Sg
Scenedesmus abundans (O.Kirchner) Chodat	++++	W-Sg
Scenedesmus intermedius Chodat	+++	A
Didymocystis bicellularis (Chodat) Komárek	+++	W-A
Tetraëdron gracile (Reinsch) Hansgirg	++	W-Sg
Bacillariophyceae		
Melosira varians C. Agardh	++++	W-Sg-A
Tabellaria sp. Ehrenberg ex Kützing	++	W-Sg
Cocconeis placentula Ehrenberg	++	Sg
Nitzschia acicularis (Kützing) W.Smith	++	W-Sg
Navicula lanceolata Ehrenberg	++	W-Sg
Diatoma vulgaris Bory	++	P
Synedra affinis Kützing	++	W-Sg-S
Synedra ulna (Nitzsch) Ehrenberg	+	W-Sg-S
Navicula pusilla (Grunow) Krammer	+	P
Navicula mutica Kützing	++++	W-Sg
Navicula viridula (Kützing) Ehrenberg	++	Sg-S
Cyclotella sp. (Kützing) Brébisson	++	Sg
Pinnularia major (Kützing) Rabenhorst	+	P
Asterionella sp. Hassall	+++	Sg
Cymatopleura sp. W.Smith	+	Sg
Zygnematophyceae		
Closterium aciculare T.West	+	Sg

Staurastrum tetracerum Ralfs ex Ralfs	++	Sg-S
Cosmarium angulosum Brébisson	++++	P
Euastrum ansatum Ehrenberg ex Ralfs	++	W-Sg
Cryptophyceae		
Chroomonas acuta Utermöhl	++	W-Sg
Cryptomonas marssonii Skuja	++	P
Chrysophyceae		
Dinobryon sp. Ehrenberg	++	P
Dinophyceae		
Peridinium sp. Ehrenberg	+++	W-Sg-S

The phytoplankton cell density observed during the second half of 2022 is much higher than that recorded during the first one (Fig.2), with a density ratio between the two periods of the year almost equal to four and whose maximum value matched with June (585.10^4 Ind.L^{-1}). In comparison, the average density recorded during the year's first half was 95.58 10^4 Ind.L^{-1}. This last observation is confirmed by the one way anova analysis, at a significance level of 0.05 the probability p=0.02084 is therefore less than 0.05, this means that there is a significant difference between the cell density recorded for the four seasons of the year, this analysis is followed by the Tukey test to assess whether the means are significantly different from each other. the results obtained showed no significant difference between the cell density obtained for the summer season and autumn, the same results are obtained for the spring and winter season.

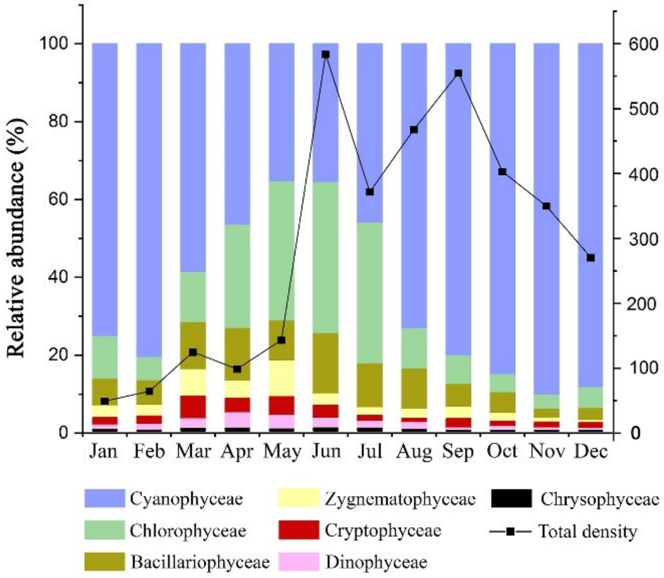


Figure 2. Cell density and the relative abundance of phytoplankton in Beni-Zid Dam water.

This monthly quantitative evolution of phytoplankton is almost the same as observed in water dams in similar region of Algeria (northeast of Algeria) (Boudjellab, 2019; Ghannam, 2019). The fast growth of the micro-algae community from June is justified by relatively high values of the euphotic zone depth, due to reduced water turbidity, as compared to the first months of the year when the high rainfall was responsible for the drainage of large quantities of suspended matter from the watershed to the reservoir waters, this greatly increases the turbidity of the water. This strong influence of water transparency on the development of microalgae has been observed even in the marine environment (Mirzaei, 2017). Other factors stimulate phytoplankton growth, such as light intensity and daily sunshine duration which are relatively high.

The seasonal quantitative and qualitative evolution of phytoplankton is a function of variations in factors such as temperature (Wassie and Melese, 2017; Yilmaz *et al.* 2017; Manamani and Bensouilah, 2023) light, nutrient contents (Yadav and Pandey, 2018; Akagha *et al.* 2020) and biological factors like grazing by zooplankton which is very abundant in the productive period (Wentzky *et al.* 2020; Freilich *et al.* 2021).

Cyanophyceae's relatively high cell density was observed throughout the study period, with a relative abundance exceeding 50% for 8 out of 12 months, and 75% for half of the study period. This dominance of Cyanophyta species weakened from April until July, in favor of other phytoplankton classes, with a very strong contribution of Chlorophyte species to the overall phytoplankton density (reaching 38.84% in June). Then come, and in descending order of annual average relative abundance come: Bacillariophyceae (8.54%), Zygnematophyceae (3.32%), Cryptophyceae (2.61%), Dinophyceae (1.75%) and finally Chrysophyceae (0.45 %).

Many studies have noted a relatively large abundance of cyanophyte species (Jindal *et al.* 2014; Jiang *et al.* 2017; Simić *et al.* 2017; Taş, 2021; Zhang *et al.* 2021; Rousso *et al.* 2022) and chlorophyta species (Zhang *et al.* 2013; Chekryzheva, 2017; Malysheva *et al.* 2018; Sharov, 2020). This dominance is considered the most significant and visible indicator of the increased eutrophication in lakes and reservoirs (Chirico *et al.* 2020; Vanderley *et al.* 2021). It results from many abiotic factors such as climate change including global warming (Paerl and Otten, 2015; Paerl, 2017; Vanderley *et al.* 2021), water transparency (Vanderley *et al.* 2021), excessive loads of phosphorus and nitrogen and ratios (Gophen, 2021; Bonilla *et al.* 2023), chemical oxidation state of inorganic nutrients (Amorim *et al.* 2020; Zhang *et al.* 2021), wind (Liu *et al.* 2019) Seasonal droughts and water level (Brasil *et al.* 2015; Tilahun and Kifle, 2019). In contrast, many authors have reported the dominance of bacillariopyceae in oligotrophic waters [16,50,52,62]. Besides, certain species of cyanobacteria are at the origin of toxic blooms (Hayes *et al.* 2020; Chorus & Welker, 2021; Gugger *et al.* 2023; Karydis, 2023) and a producer of bad tastes and odors, in drinking water (Suurnäkki *et al.* 2015; Watson *et al.* 2016).

Barroin (1999) explains the phenomenon of the different algal species proliferation, coinciding with the beginning of spring by the increase in the illumination and the start of water thermal layering. It uses abundant nutrients, and is hardly consumed by zooplankton. This spring phytoplankton consists mainly of Chlorophyceae and diatoms (Barroin, 1990).

3.2. Monthly evolution of the phytoplankton diversity indices

The Shannon-Wiener index (*H'*) is used to assess the diversity of an ecosystem based on a given organism community. An undiversified environment with the dominance of a single or a few species is characterized by a value of H' less than 2.5 bits.Ind^{-1}. On the other hand, if H' exceeds 4 bits.Ind^{-1}, the natural environment is described as isotropic, where the species tend towards equiprobability. In our work, H' ranged from 2.32 to 3.94 bits.Ind^{-1}, indicating a medium richness of phytoplankton species.

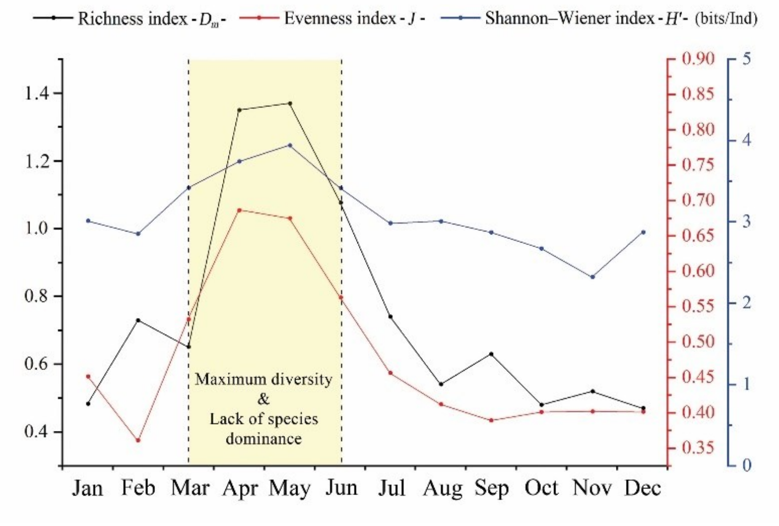


Figure 3. The monthly evolution of the Margalef richness index, Pielou evenness index, and the Shannon–Wiener index, calculated for the phytoplankton community found in the Beni-Zid dam waters.

Moreover, from March to June, the values calculated for the Pielou regularity index (P) exceeded 0.5, indicating a relatively homogeneous distribution of phytoplankton cells observed on the listed species. Outside this period, *P* took values lower than 0.5, with a minimum recorded in February ($P_{Min} = 0.36$), indicating a quantitative dominance of a small number of species or even a single species at the expense of others. Figure 2 shows a high abundance of cyanophyte species, exceeding 80% of the overall microalgae density from September to December. This is further supported by the results of the Margalef index (D_m) calculation, which indicates the highest species richness during the period marked in yellow in Figure 3, from March to June and reaching a maximum richness in May with a $D_{m.Max}$ of 1.37, while the lowest richness is noted in December with $D_{m.Min}$ of 0.47. This is consistent with the results obtained by Zhang et al. (2014) working on the Macau dam in China, following the calculation of the Shannon and Wiener, the Simpson and the evenness indices, it was found that there is a maximum phytoplankton diversity extending over a period from March to June; beyond this period, diversity decreases progressively (Zhang *et al.* 2014).

Despite the high cell density values recorded from June to December, the number of species observed during this period of the year, was the lowest. This can be explained by the development of a limited number of species, especially those belonging to Cyanophyceae and Chlorophyceae, which tend to dominate the phytoplankton population. While in the months from May to June, the phytoplankton population was the most diversified. It should be noted that the seasonal succession of species groups is the consequence of the fluctuations effect of environmental factors on the phytoplankton community (Muhtadi *et al.* 2020).

This negative correlation between cell density and specific richness of phytoplankton was also observed by Baykal et al. (2011) during their work on the waters of the Melen River in Turkey (BAYKAL *et al.* 2011).

They noted that the lowest values of the specific richness coincided with an efflorescence of *Peridinium* sp. Tracanna et al. (2006) confirmed these same results, who indicated that the maximum values of the population matched with the minimum values of diversity; where the numerical growth of phytoplankton is generally due to the intense proliferation of a very small number of species (Romero *et al.* 2006). Other authors explain the variation in species richness by factors other than the dominance of certain species, such as anthropogenic chemical stress, which stimulate the development of several species at the same time, thus increasing the specific richness of the polluted site (Carlson and Simpson, 1996; Su *et al.* 2017), and also to the withdrawal of significant quantities of water from dams, intensively modifying the structure of the phytoplankton community (Zhang *et al.* 2013; Song *et al.* 2023).

3.3. Evaluation of the trophic state of water

The monthly dosage of the Chl-a, SD, TP, and TN parameters allowed the calculation of $TSI_{Chl\text{-}a}$, TSI_{SD}, TSI_{TP}, and TSI_{TN}, respectively. The results obtained for these indices are illustrated in Figure 4, which shows TSIs varying between the value 50 and 70 during almost the entire study period, this indicating a eutrophic state of the dam water, with a tendency for blue-green microalgae to dominate the existing phytoplankton community (Carlson and Simpson, 1996).

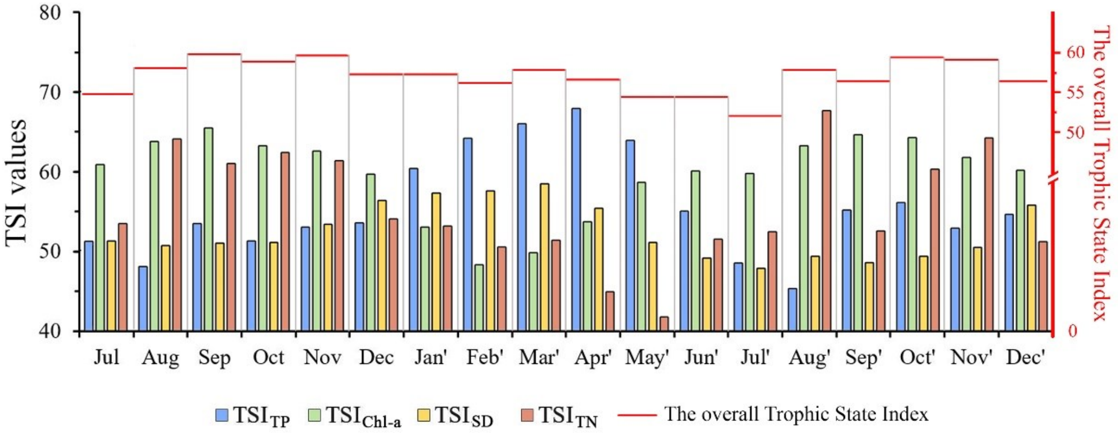


Figure 4. Monthly evolution of the four types of TSIs and the overall TSI. The months of 2022 are marked by the symbol ('), and those of 2021 are without.

Furthermore, to highlight groups of months with similar deviation results between the different calculated TSIs, a Hierarchical Cluster Analysis was performed (Fig. 5). This allows us to note four groups of months, the first one (G1) grouping the months of August, October and November; the second group (G2) including June, July, September and December; the third group (G3) includes January, February and March and the last group (G4) including the 2 months of April and May.

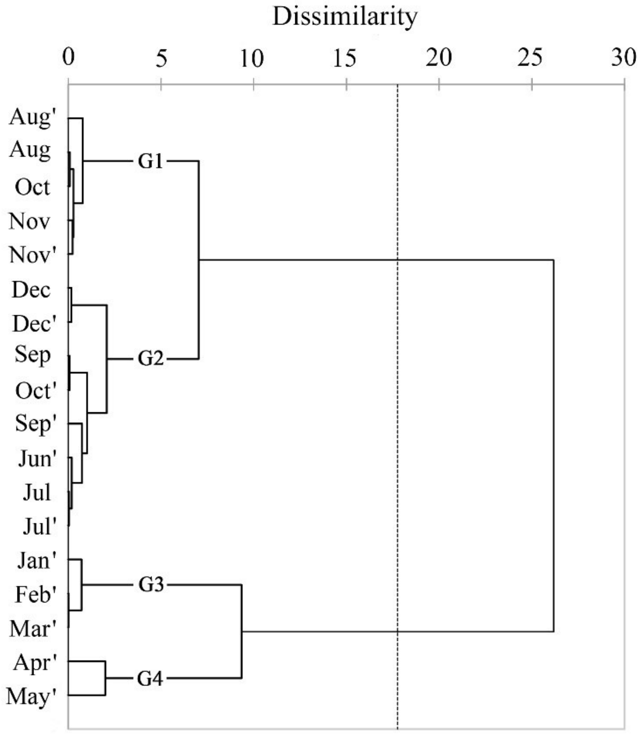


Figure 5. Cluster analysis grouping months by calculated deviation between the different TSIs. The months of 2022 are marked by the symbol ('), and those of 2021 are without, and (G: Group).

These four groups of months are circled in Figure 6, representing a two-dimensional projection of the principal components analysis (PCA), applied to the data of monthly deviations calculated between the different TSIs.

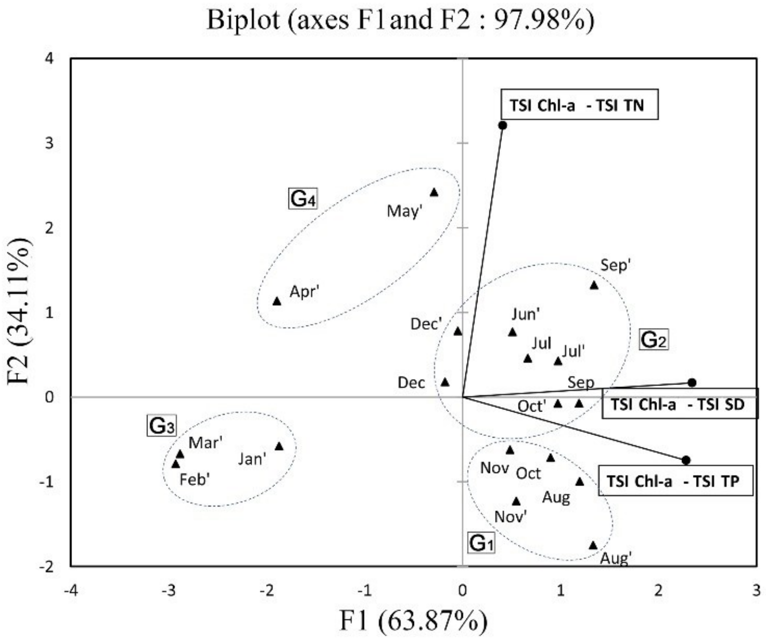


Figure 6. The Principal component analysis plot illustrates the correlation between the deviations of the trophic state indices in the dam's water and the distribution of the months according to these deviations. The months of 2022 are marked by the symbol ('), and those of 2021 are without, and (G: Group).

According to the graphical representation of the PCA (Fig. 6), there is a positive correlation between the deviation obtained from the subtraction of the TSI_{Chl-a} from the two other TSI (TSI_{SD} and TSI_{TP}). This indicates that when the attenuation of light in the water body of the dam is due to the intensive development of phytoplankton cells ($TSI_{Chl-a} - TSI_{SD} > 0$) (Carlson and Simpson, 1996), it is accompanied by a limitation of phosphorus element for microalgae growth ($TSI_{Chl-a} – TSI_{TP} > 0$) (Carlson and Simpson, 1996). According to the ACP, this situation coincides with group 1 (August, October and November) and to a lesser extent with the second group of months (June, July, September and December). Opposite conditions are observed during the 3rd group of months (January, February and March) with an attenuation of water transparency mainly due to non-algal particles of mineral type ($TSI_{Chl-a} - TSI_{SD} < 0$) made abundant in this period of the year by the discharge into the dam of large quantities of rainwater crossing the catchment area (Liu *et al.* 2017; Bilgin, 2020; Savira Agatha Putri *et al.* 2020; Qin *et al.* 2020), and an absence of phosphorus element limitation ($TSI_{Chl-a} – TSI_{TP} <0$).

This aligns with the results obtained by Lin et al. (2022), who reported an excess of phosphorus and non-algal turbidity in the water during the winter season (Lin *et al.* 2022). In contrast, Mamun and An 2017, indicate that most water reservoirs show a dominance of large particles affecting water turbidity and a limitation in phosphorus during the period when phytoplankton development is at its peak (Mamun and An, 2017). In our case, this coincides with the months of August to November.

The nitrogen element limitation (TSI_{Chl-a} - TSI_{TN}) was proven to be totally independent of the phosphorus element limitation and the light attenuation factor in the water body. This is represented in Figure 6 by an almost right angle between the projection of the TSI_{Chl-a} - TSI_{TN} deviation and the other deviation types. Furthermore, when there is an excess of available phosphorus, nitrogen becomes the dominant factor regulating the trophic state of the waters (Xu *et al.* 2014; Paerl *et al.* 2016). This Nitrogen-Phosphorus relationship is often used in the form of a ratio (TN/TP) to determine the states of limitation in these elements for the growth of microalgae in freshwater ecosystems (Maberly *et al.* 2020).

Some recent studies aim to develop sensors and algorithms which can be used in various fields such as environmental monitoring (weather, water quality and pollution) (Subramanian *et al.* 2024; Venkatraman *et al.* 2024), agriculture (monitoring of crops, soil fertility, and soil moisture to optimize agricultural irrigation) , and disaster Management (Surendran *et al.* 2023; Selvanarayanan *et al.* 2024; Sundarapandi *et al.* 2024).

In the context of this study, these sensors can be essential tools for monitoring the quality of surface waters in real time and with precision. They enable the measurement of a range of chemical parameters, such as nutrient concentrations like nitrates and phosphates, or even tracking the proliferation of toxic algae by measuring chlorophyll or cyanotoxins (Wang *et al.* 2015; Keith *et al.* 2018; Priyanka *et al.* 2024).This work allowed, for the first time, to note a dominance of blue-green algae on the other classes of phytoplankton, knowing that the water of the dam is used for the supply of drinking water for nearly 85,000 inhabitants, this is worrying on two levels, the first is that some of these species are potentially toxinogenic; and secondly, the dominance of this class of microalgae indicates a tendency of water to eutrophicate more and more. This alarming situation is comparable to that observed for other dams in the same region in Algeria. The study of the deviations of the different TSIs allowed to emphasize the role of the phosphorus element limitation for the phytoplankton growth, this insites the local authorities managing and monitoring the quality of the waters, give particular importance to this element in the Beni-Zid dam.

Future steps of this study could focus on extended multi-year studies to capture interannual variations influenced by climatic and hydrological changes. Monitoring specific bioindicators, such as *Microcystis aeruginosa*, and tracking cyanotoxin production could help predict and mitigate harmful algal blooms. Practical applications include developing strategies to reduce nutrient inputs, implementing early warning systems for algal blooms.

Acknowledgements

The authors would like to express their appreciation to the University of 20 August 1955 in Skikda, Algeria, for providing the necessary resources for this work.

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