Comparative study of the diversity and distribution of crustacean communities in three freshwater biotopes (Tonga, Birds and El Kennar lakes) located in northeastern Algeria.

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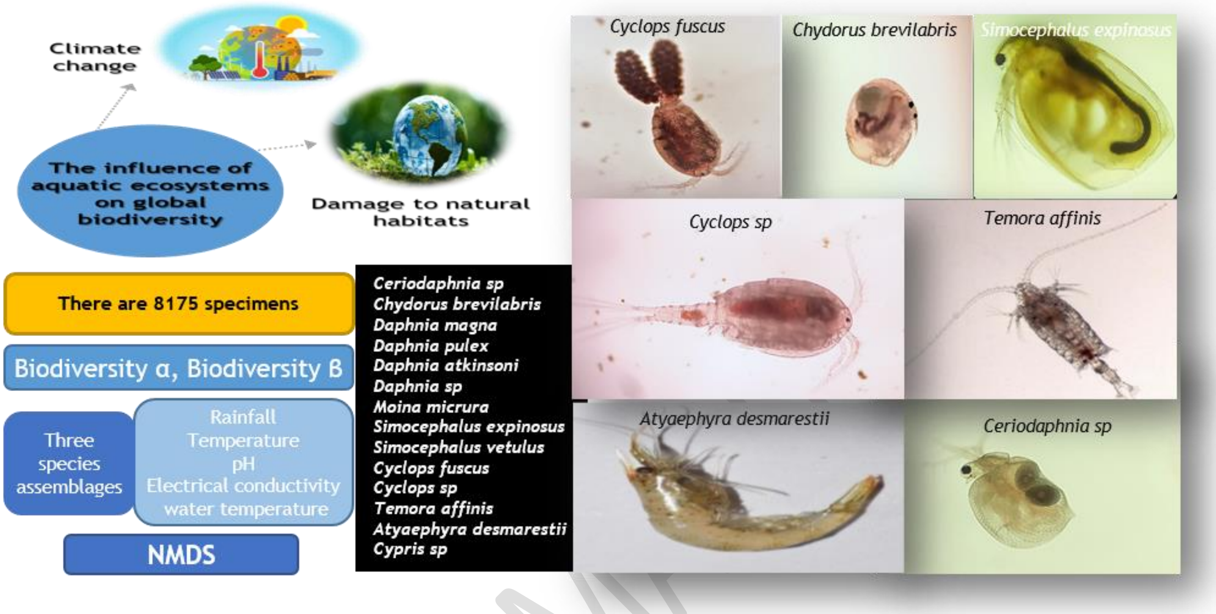
Graphical abstract



Abstract.

The crustacean group is a keystone species that plays a significant role in the aquatic ecosystem by participating as decomposers or consuming detritus. Understanding the ecology and spatiotemporal distribution of crustaceans' communities is crucial for the effective management of the species and the associated structural and functional services that they provide in freshwater ecosystems. This study focused on freshwater crustaceans' communities from northeastern Algeria, located over a distance of 337 km. The objective of this research is to present data on the distribution and composition of the communities, evaluate both α- and β-diversity, and identify underlying potential factors or parameters that can serve as baseline data for future studies pertaining to global changes. From May 2022 to April 2023, the target crustacean populations were sampled every two months from Tonga Lake (El Kala National Park), Birds Lake (El Tarf province), and El Kennar Lake (Jijel province). A total of 8,175 specimens were sampled and inventoried; 14 species were identified belonging to 9 genera: 9 Cladocerans species, 3 Copepods species, one species of Ostracods and another of Decapod. The recorded taxa match 7 families: Daphniidae, Cyclopidae, Cyprididae, Atyidae, Chydoridae, Temoridae and Moinidae. The non-metric multidimensional scaling (NMDS) ordination analysis showed a clear spatial effect in the crustacean communities and highlight three distinct species assemblages between lakes. The NMDS also showed possible effects of rainfall, temperature, pH, electrical conductivity, and water temperature on community composition and distribution. Furthermore, the most abundant species were *Cypris sp* (40.36%), *Cyclops fuscus* (38.10%), and *Simocephalus expinosus* (56.19%) in Tonga Lake (*S*= 9), Birds Lake (*S*= 9), and El Kennar Lake (*S*= 10), respectively. The Shannon index showed similar levels of diversity, with the highest value in Tonga Lake (*H'*= 2.48, moderate level of diversity). The Pielou evenness index also showed higher equitability in both Tonga and Birds lakes than in El Kennar one; this latter recorded the highest species abundance (*A*=

3,771). According to Sorenson's coefficient, our communities have quite a bit of overlap (from 63% to 78% of similarity). Our research essentially confirms the hypothesis that global changes and possibly biotic and physical processes may have an effect on the biodiversity and composition of crustacean communities in Algeria. The functional diversity and the interactions with environmental factors, from global to local scales should be studied in our ongoing project concerning our local crustaceans' communities that are still poorly documented.

Keywords: Biodiversity; crustaceans; ecological indexes; freshwater ecosystems; NMDS ordination; physicochemical parameters.

1 Introduction

Biodiversity is particularly noteworthy in freshwater ecosystems. They are the most dynamic, with a high number of species (Rolls *et al*. 2018). Freshwater habitats occupy, 1% of the Earth's surface, yet are hotspots that support, 10% of all known species (Strayer and Dudgeon 2010). Freshwater crustacean communities play an important role in nutrient cycling and the transfer of energy from primary producers to higher trophic levels in aquatic food systems as herbivores, detritivores, predators and prey (Lomartire et al. 2021). They also serve as biological indicators for assessing surface water quality (Krepski et al. 2024). However, they are subject to unprecedented levels of human disturbance, with varying degrees of impacts on water, sediments and biota. Biomonitoring of these communities has therefore become a widely accepted and irreplaceable tool for ecological conservation and management of aquatic ecosystems (Xiong et al. 2020). Their short reproductive cycles make them responsive to environmental changes, making them effective indicators of climate change (Beaugrand et al. 2015).

Crustaceans originated ~ 500 million years ago during the Precambrian period (Zhang et al. 2007). Although most crustaceans are aquatic and free-living, some are terrestrial (e.g., woodlice) or parasitic (e.g., fish lice). They are the most species-rich group of marine animals, living from the deepest ocean areas to muddy wetlands (Wacker and Harzsch 2021). There are approximately 150,000 species exist in the worldwide, of which only 52,000 have been described (Mahmood Ghafor 2020). There are four primary clades of crustaceans: Branchiopoda (e.g., Anostraca, Notostraca, and Phyllopoda) (Walossek 1993), Maxillopoda (e.g., Copepoda, Branchiura and Cirripedia) (Suárez-Morales 2015), Malacostraca (e.g., Eumalacostraca, Hoplocarida) and Ostracoda (e.g., Myodocopa, and Podocopa) (Schwentner et al. 2017). In addition, crustaceans contain two minor clades, Remipedia and Cephalocarida (e.g., horseshoe shrimp), each of which contains 12–17 species (Schwentner et al. 2017).

The concept of biodiversity hotspots pioneered by ecologist Norman Myers as a template for setting global conservation priorities (Myers et al. 2000). The map of hotspots overlaps extraordinarily well with the map of the natural sites that are most beneficial to humanity (Pimm and Raven 2020). Hotspots are some of the richest and most important ecosystems in the world, and are home to many vulnerable populations whose survival depends directly on nature (Myers et al. 2000). They are particularly sensitive to human disturbance and much of their remaining high-quality habitat persists only within protected areas (Mittermeier et al. 2004). According to one estimate, although they represent 2.5% of the Earth's surface, forests, wetlands and other ecosystems (Barrett et al. 2016), in hotspots are responsible for 35% of the 'ecosystem services' on which vulnerable human populations depend. This is why Conservation International has adopted the idea of protecting these incredible areas known as 'hotspots'. Today, the mission has expanded beyond protecting hotspots. Because it is not enough to protect species and places; for humanity to survive and flourish, protecting nature must be a fundamental part of every human society (Brooks et al. 2006).

Mediterranean wetlands identified in the regional context as 'biodiversity hotspots' (Cañadas et al. 2014). They play a key role in supporting an exceptional diversity of plant and animal species, many of which are endemic and rare. This makes them one of the most diverse ecosystems on the planet (Rifai et al. 2018). The freshwaters of the circum-Mediterranean countries are indeed known for their exceptional biodiversity, housing. Thirty-five percent of Palearctic freshwater species and more than 6% of the world's freshwater species with a high rate of endemism (Tierno de Figueroa et al. 2013). The exceptional diversity of freshwater fauna of the Mediterranean Basin currently faces a crisis in which climate change combined with overexploitation of freshwaters heavily threatens the local fauna (Ayati et al. 2023). Recent studies have shown that physical and chemical alterations can have adverse impacts on biota (Krepski et al. 2024). These alterations include sewage discharge (Tripathi et al. 2023), elevated water temperatures due to thermal pollution (Poole and Berman 2001), and increased river salinity resulting from mining activities (Slugocki and Czerniawski 2023). Thus, environmental parameters play a pivotal role in influencing the presence and spatial distribution of zooplankton (Umi et al. 2024). Responses of crustaceans to climate variability and change are not uniform and vary depending on the species, life-history stage, reproductive status, and geographical distribution (Azra et al. 2022). Fluctuations in crustaceans populations are influenced by various factors, such as temperature, phytoplankton and the density of predators, particularly fish species (Gouws et al. 2010).

Algeria is characterized by a climate that is extremely favorable to the wide distribution of crustaceans. Lucas conducted previous studies on Ostracods (1849), followed by Moniez. (1891), Gauthier (1928a, b, and c), Gauthier and Brehm. (1928) and De Deckker (1981). No further work was carried out until the study by Samraoui et al. (1998), which provided checklists of species of Rotifers, Cladocerans, Copepods and Ostracods from Numidia, in the north-east of Algeria. More recently, the two studies of Ghaouaci et al. (2017 and 2018) including non-marine living Ostracods, Cladocerans and Copepods from the continental waters of Algeria. Our study provides the first comparative analysis of crustacean species living in different ecoregions of Algeria. It fills an important gap in regional biodiversity research. We applied useful and powerful ecologic analysis by using many R packages to differentiate species' assemblages: NMDS analysis and DER algorithm. The Numeric Ecology provides more technics to characterize the fauna and the flora structure and composition. While previous studies in Algeria have mostly focused on individual sites (e.g., Lake Tonga, Birds Lake, or isolated branchiopod records), present work integrates data from different habitats to identify broader ecological patterns. On a worldwide scale, this study contributes to freshwater biodiversity research by providing new information on how crustacean assemblages respond to ecological gradients in North Africa, a poorly studied region that can improve global understanding of biogeographic distribution and conservation priorities.

Unfortunately, the diversity and distribution of the crustacean species in Algeria have not been reported in detail and research on crustacean diversity is rarely carried out (Ayati et al. 2019). Given the important role of the crustacean group in the freshwater ecosystems especially in Tonga, Birds and El Kennar lakes, it is important to study crustacean diversity in many Algerian ecoregions. We hypothesized that crustacean community composition could prove fine-scale variation in biotope types and water quality because crustacean species could respond typically to environmental gradients. Thus, the purpose of this study was, firstly, to determine the diversity and distribution of the crustacean taxa along a geographic transect in the north-eastern of Algeria to appraise both α- and β-diversity levels, secondly, to contribute to the conservation and monitoring of the freshwater ecosystems as a precious resource.

2 Material and methods

2.1 Study area

The study took place during May 2022-April 2023 period and was conducted in the north-eastern region of Algeria in order to cover spatial and temporal changes in the crustacean community. Three specific lakes were selected to carry out sampling operations (Figure 1).

-Tonga Lake (36°53′1.03″ N, 8°31′46.60″ E) is a 2,600 hectares freshwater wetlands connected to the Mediterranean Sea by the artificial Strait of Messida. Although, it is within the boundaries of the El Kala National Park under the Ramsar Convention (1983). This site was selected due to its recognition as a key Ramsar site with limited existing data on crustacean communities. The 2016 study remains one of the few providing quantitative information on the prevalence of these organisms within macroinvertebrate assemblages.

- Birds Lake (36°47′ N 08°7′ E), covering 150 hectares, has been a Ramsar site since 1999, known for its biodiversity. It forms part of a larger wetland complex in eastern Algeria, much of which is designated as a national park. Tonga and Birds lakes are located in El Tarf province. This site was selected because it hosts various crustacean groups, including Cyclopidae (cyclopoid copepods), Daphnidae (cladocerans), and Cyprididae (ostracods), highlighting its ecological importance in Algerian freshwater habitats.

- El Kennar Lake (36°48′ N; 05°57′ E), also known as Ghedir Béni Hamza, is located to the east of Jijel province and covers an area of approximately 36 hectares. This site was chosen because it represents a vulnerable aquatic ecosystem that is heavily impacted by anthropogenic pressures, particularly urban and agricultural contamination, making it valuable for studying human-induced effects on crustacean communities.

This study focuses on the Algerian region, where we worked over a distance of 300 km as the crow flies and respected the distance between the three lakes. In addition, the crustacean biodiversity of Algerian freshwater is underestimated, and further research is needed to supplement and deepen the current conclusions.

2.2 Sample collection

To cover a broad range of taxa, samples of crustacean specimens were collected every two months from May 2022 to April 2023. The freshwater was characterised on the basis of several physicochemical parameters such as temperature (T) in °C, pH and conductivity (EC) in µs/cm, measured by a multi-parameter water analyzer (HI 9829). Temperature and rainfall data were kindly provided by the Agricultural Services of El Tarf and Jijel provinces (Table 1). Bimonthly sampling is sufficiently regular and more accurate for monitoring changes in communities, as it allows intermediate transitions between seasons to be captured. It thus offers a better balance between ecological representativeness and field constraints.

Each station was defined as a research area delimited by GPS. Within each area, samples were taken at random using a hand net (300 µm mesh) on the shore for an area of 1 m² (Decapoda) and a plankton net (64 µm) in the pelagic zone with a volume of 1 L (microcrustaceans), using a standardized effort (same number of net hauls or net pulls per site). This protocol ensured that the sampling effort remained constant across the three sites in each lake, reduced biases related to environmental variability, and provided comparable data between the different ecosystems studied.

2.3 Laboratory analyses

Samples were collected from 3 stations in each lake for crustacean inventory. Sampling methods should be adapted to the habitat and the group to be studied. According to. Mack et al. (2012), qualitative samples of freshwater crustaceans were collected using a hand net measuring 64 µm, which effectively captured all zooplankton groups, and they were preserved immediately in 70% ethanol solution in polyethylene bottles. In the laboratory, the specimens of crustaceans were examined using a Olympus microscope CH20 for a dissection, small entomological pins can be mounted. The dissection can be easily performed if a specimen is placed on the slide with glycerin (or other viscous medium).

Ostracods specimens were dissected under a microscope. The valves were opened and the soft body extracted in order to isolate the various appendages (antennae, walking legs, cleaning legs, uropod, maxillipeds, maxillules, mandibles, fork, and male copulatory organs), all of which are necessary for taxonomic identification by Meisch. (2000).

Cladocerans were dissected using entomological needles in a glycerin solution in order to observe the details of the antennules and rostrum, or the details of the spinulation of the dorsal edge of the ephippium or on the edges of the carapace, cephalic shield, and thoracic limbs. Using as a reference the contribution of Błędzki and Rybak (2016).

Copepods were dissected under a microscope using fine needles on semi-permanent slides, using a glycerin solution to separate the different body parts such as the double genital somite, caudal rami, antennules, labrum, mandibles, maxillary palps, maxillae, and maxillipeds (Błędzki and Rybak 2016)

Shrimps identified according to morphological criteria (body shape, size, and coloration; number of rostral teeth; degree of abdominal development and its relative position in relation to the cephalothorax; presence or absence of a keel and tooth on the abdominal segments; and finally, shape and length of the antennae and antennules) according to Fischer et al. (1987).

2.4 Statistical analysis

All our statistical analyses were performed using R, version 4.4.1 (R Core Team 2024; Ihaka and Gentleman 1996) and RStudio (Posit Team 2024) for Windows. Shapiro-Wilk test was used to test variables normality. The main aim of this survey is to characterize both α- and β-diversity levels of the crustacean communities in freshwater ecosystems. Shannon *(H')* diversity index and Pielou's evenness index *(J')* were calculated using *'EcoIndR'* package

(Gonzalez 2023). We also calculated the Sørensen similarity index to assess the quotient of similarity for two communities based on the number of species in each community and the number of species in common. This index varies between 0 (no overlap) and 1 (perfect overlap). In an ecological context; no one diversity index can adequately summarize species diversity and for this reason we used the DER algorithm (Gonzalez 2023) in our study to estimate multiple diversity indexes and for comparing crustacean species diversity between assemblages. All indexes were transformed to a scale range of 0 to 1, and the algorithm calculated the polar coordinates of all samples with all possible combinations for all indexes and other ecological descriptors. This algorithm provides tools for differentiating assemblages on the basis of many diversity indexes. The DER algorithm was applied to maximize dispersion among our three freshwater biotopes. Also, we can determine the differences in terms of rarity, abundance, heterogeneity, richness, evenness and diversity among assemblages. To investigate the crustacean species assemblages; we carried out also a multivariate analysis by applying a Non-metric MultiDimensional Scaling (NMDS) as a distance-based ordination technique. Because it focuses on the distance matrix, it is very flexible and any distance measure can be used. As usual, the data matrix (n sample units × p species) is converted into an $n \times n$ distance matrix (or a dissimilarity matrix). The NMDS algorithm was performed bu using '*vegan*' R package edited by Oksanen et al. (2025). Finally, we also examined, by an ombrothermic diagram, the relationship between temperature and precipitation to determine the length of dry, wet, and extremely wet periods in the selected geographical regions. Data were expressed as mean ± standard error (se). Several R packages were also used in our statistical analysis and to plot data results such as '*ggplot2*' (Wickham 2016), '*ggcorrplot*' (Kassambara 2023a), '*webr*' (Moon 2020). '*Hmisc*' (Harrell 2025), '*ggpubr*' (Kassambara 2023b), '*PMCMRplus*' (Pohlert 2024), '*dunn.test*'

(Dinno 2024) and '*psych*' (Revelle 2024). All these R free-packages are also available on CRAN web site (The Comprehensive R Archive Network: https://cran.r-project.org).

3. Results

3.1 Crustacean species composition

In general, a total of 8,175 individuals of crustaceans were recorded at the Tonga, birds and El Kennar lakes, which included 14 species of freshwater crustaceans belonging to 9 genera (*Ceriodaphnia, Daphnia, Simocephalus, Chydorus, Moina, Cyclops, Temora, Cypris* and *Atyaephyra*) and 7 families (Daphniidae, Temoridae, Cyclopididae, Atydae, Chydoridae, Cyprididae and Moinidae). Nine species were reported from Cladocera group, 3 species from Copepoda and one species was reported from Ostracoda and Decapoda group (Figure 2).

In our study, the Cladocera group was represented by *Chydorus brevilabris* (Frey), *Ceriodaphnia sp, Moina micrura* (Kurz), *Daphnia magna* (Straus), *Daphnia pulex* (Leydig), *Daphnia sp, Daphnia atkinsoni* (Braid), *Simocephalus expinosus* (Koch) and *Simocephalus vetulus* (Müller). Moreover, the Copepoda group was represented by *Cyclops fuscus* (Jurine), *Cyclops sp* and *Temora affinis* (Poppe), and the Decapoda and Ostracoda groups were represented by the lowest number of taxa, namely *Atyaephyra desmarestii* (Millet) and *Cypris sp.*

Pie graphs illustrate the percentages of taxa and taxonomic composition of the crustacean communities in Tonga, Birds and El Kennar lakes (Figure 3). It can be seen that the highest richness, in the different sampling sites, of freshwater crustaceans was recorded in El Kennar Lake (10 species with 3,771 specimens); the lowest one was recorded in Birds Lake (9 species with 3,345 specimens) followed by Tonga Lake (9 species with 659 specimens). Furthermore, the species *Cypris sp* was the most abundant (40.36%) in Tonga Lake, while *Cyclops fuscus*

(38.10%) and *Simocephalus expinosus* (56.19%) species dominated in Birds and El Kennar lakes, respectively.

3.2 Ecological indexes

In ecology, the conception of species diversity is used to assess the facility of the communities to maintain itself stable; even though it gets disturbed. In this sense, the diversity level of crustaceans' assemblages in our three freshwater biotopes was estimated using the Shannon index *(H'),* Pielou's evenness index *(J')* was also calculated to evaluate how the 14 species are evenly distributed in our communities related to the three lakes.

In Figure 4, it can be seen that the diversity of our crustacean communities in the three distinct biotopes is in the medium category of the biodiversity Shannon's index; this latter varies from *H'*= 2.10 to *H'*= 2.48. We also conclude that Tonga Lake is the most diverse lake despite its low species' abundance (as shown by Figure 4). Regarding to the Pielou's eveness index, the highest value was recorded in Tonga Lake (*J'*= 0.78) and the lowest one was recorded in El Kennar Lake (*J'*= 0.63); these results mean that Tonga an Birds lakes have more equitable distribution of their species; however the El Kennar Lake is characterized by the highest dominance rate of species which is *Simocephalus expinosus* (56.19%), as shown in Figure 3.

As mentioned in the materials and methods section; we used the DER algorithm for differentiating samples on the basis of several ecological indexes that better reflect the dispersion among species assemblages. The DER algorithm is used in ecological surveys because sometimes no one diversity index can adequately summarize species diversity. All indexes were transformed to a scale range of 0 to 1, and the algorithm calculated the polar coordinates of all samples with all possible combinations for all indexes and other ecological descriptors (as abundances). This algorithm provides tools for differentiating assemblages on the basis of many diversity indexes; the DER algorithm result is resumed by the Figure 5 and show the similarity level between crustacean communities.

For further investigation, in our survey, the idea of the NMDS analysis is to specify the original positions of the crustacean communities in multidimensional space and to define the number of reduced dimensions (typically 2). The ordination plot (Figure 6) presents an excellent representation of our samples in reduced dimensions because the recorded stress value is equal to 0 (<0.2). As expected, the ordination study of the crustacean species assemblages was conclusive about the diversity and composition in El Kennar, Tonga and Birds lakes. Obviously, Tonga Lake is more characterized by *A. desmaresti* and *T. affinis* species while, *Cyclops sp.*, *M. mircura* and *S. vetulus* species correspond more to Birds Lake. By contrast, El Kennar Lake is more marked by the presence of the following species: *Daphnia sp*, *Ceriodaphnia sp.*, *D. attkinsoni* and *C. brevilabris.*

In conclusion, NMDS analysis showed that the three lakes were clearly separated according to their crustacean communities. The 1st axis (NMDS1) separated El Kennar Lake (*S*= 10, *A*= 3,771) and Birds Lake (*S*= 9, *A*= 3,745) from Tonga Lake (*S*= 9, *A*= 659); whereas the 2nd axis (NMDS2) distinguished very well the analyzed lakes. The NMDS ordination revealed an overlap between the three communities; this is justified by the presence of common species. This result is supported by the Sørensen index, which reflects the level of similarity between crustacean communities: 63% between Tonga/El Kennar lakes (6 species in common), 74% between Birds/El Kennar (7 species in common) and 78% between Tonga/Birds lakes (7 species in common). Additionally, the NMDS ordination plot shows, firstly, a significant effect of the rainfall on the species composition in El Kennar Lake, secondly, a notable effect of both water temperature and conductivity on species composition in Tonga Lake, and thirdly, a possible effect of water pH on species composition in Birds Lake.

3.3 Climatic data and physicochemical parameters

The temperature and rainfall data obtained from the regional weather stations are presented by the ombrothermic diagrams which are shown in Figure 7 for both Jijel and El Tarf provinces from May 2022 to April 2023. The two studied geographic regions showed a relative uniform climate characterized as mild Mediterranean. The yearly average rainfall was 62.95 (with a maximum of 228 mm) and 42.00 (with a maximum of 73.00 mm of maximum) mm in Jijel and El Tarf provinces, respectively. This observation states that the geographic region of El Tarf is more dry than in Jijel. Annual average temperature was 20.83 °C in the geographic region of El Tarf and 18.83 °C in the geographic region of Jijel. The hottest months were 26.00 and 30.00 °C in Jijel and El Tarf geographic regions, respectively. These climatic characteristics could impact the distribution and abundances of the crustaceans' communities in their biotopes.

The results related to data analysis of the physicochemical parameters are shown in Table 1. The comparisons were carried out by Kruskal-Wallis test followed by Dunn's test for *post hoc* pairwise comparisons. The results showed that there is a significant difference ($p< 0.05$) between the studied lakes only for conductivity parameter. On the other hand, there were no significant differences ($p> 0.05$) between lakes for temperature and pH parameters.

4. Discussion

Biodiversity assessment is a fundamental requirement for the efficient management of species and the structural and functional benefits they provide in freshwater ecosystems, including wetlands (Cantonati et al. 2020). As biodiversity loss has become an urgent global issue over the past decade, for this reason, recent research has rekindled interest in biodiversity in these environments (Tickner et al. 2020). While the earliest models of biodiversity response often examined a single metric at one spatial scale, most commonly examining species richness within local communities, contemporary biodiversity research typically uses multiple diversity metrics. These include the number of species in a local community (α-diversity), compositional differences between local communities (β-diversity), and total species diversity within landscapes (γ-diversity) (Anderson et al. 2011).

North Africa is confronted with extreme conditions of drought and high temperatures that make them even more vulnerable to climate change, with serious consequences on biodiversity and ecosystem stability (Zouggar et al. 2023). This is one of the regions overlooking the Mediterranean Sea, which has been considered one of the main hotspots of climate change, suffering from water scarcity, overexploitation, saline intrusion in coastal aquifers due to sea level rise, and reduced resources (Sharan et al. 2023). According to the recent Assessment Report on "*Climate and Environmental Change in the Mediterranean Basin*" published by Cramer et al. (2022), the Mediterranean is warming 20% faster than the global average. Consequently, this region is well-defined as a hotspot area based on both current observations and future projections (Urdiales-Flores et al. 2023).

Given the high population growth in the northern part of Algeria, combined with industrial development and climate variability, the pressure on water resources is considerable (Nemer et al. 2023). Furthermore, as crustacean biodiversity is essential for maintaining ecosystem functions, it is imperative to study the distribution of organisms and their response to climate change and human disturbance. We have therefore chosen to study the abundance and distribution of crustacean communities in wetlands (Tonga Lake and Birds Lake) classified as Ramsar sites and UNESCO World Heritage Biosphere Reserves (1983, 1999) in El Kala and El Tarf provinces, and in geographical areas rich in flora and fauna such as El Kennar Lake in Jijel province. This work enabled us to identify 8,175 specimens belonging to the freshwater crustacean groups Cladocera (9 taxa), Copepoda (3 taxa), Ostracoda (1 taxon) and Decapoda

(1 taxon). Six species (*D. magna, D. pulex, S. expinosus, S. vetulus, C. fuscus,* and *Cypris sp*) were found to be common to the three lakes. The *C. brevilabris* species collected from Jijel is a new species in Algerian Cladoceran fauna. Thus, by adding these taxa to the 23 species of Calanoides identified in North Africa to date and the 13 species already known in Algeria (Mouelhi et al. 2000), it should be noted that the species *T. affinis* was recorded for the first time in this study.

In their natural environment, crustaceans' communities are generally governed by abiotic factors such as salinity, sediment characteristics, substrate, temperature, availability, water flow, flood frequency and pH (Salleh-Mukri and Shuhaida 2021). Pollution by liquid and solid waste is also an abiotic factor that greatly influences the abundance of crustaceans. Biotic factors are linked to the diversity of associated flora and fauna. In addition, human harvesting contributes to the abundance of certain species of crustaceans (Indarjo et al. 2020). Although often small, some crustacean species can be hyper-abundant and dominate the biomass of an ecosystem, such as planktonic copepods, which are considered one of the most abundant metazoans on the planet (Behringer and Duermit-Moreau 2021).

The examined ecological indexes indicated that the three biotopes are somewhat different. According to the abundance of crustacean populations, there is a gradient of decreasing abundance: El Kannar Lake has 3,771 individuals, Bird Lake has 3,745 and Tonga Lake has 659 individuals. Given the number of individuals collected, abundance in Tonga Lake is low, probably due to the characteristics of the habitat such as lack of food, competition, vegetation type, the presence of cyanobacteria, waste and pollution (Djabourabi et al. 2017). In addition, floods and droughts might influence zooplankton dynamics by affecting both local (food availability) and regional (increasing connection and dispersion) environmental conditions. Also, the levels of nutrient salts recorded as well as the indicator germs of fecal contamination are quite important and confirm the state of eutrophication in Tonga Lake (Loucif and

Chenchouni 2024). Although El Kannar Lake recorded the highest individual abundance. Furthermore, Cladocerans predominate over the other two lakes, suggesting that the water in El Kannar Lake favors the presence of Cladocerans in contrast to Tonga Lake, which favors the presence of Ostracods and Decapods. Birds Lake is characterized by intermediate dominance. The water degradation of Birds Lake is a reality and represents a serious environmental problem due to domestic wastewater discharges into the lake and intensive livestock farming around the lake (cattle and sheep), as well as very significant fecal contamination expressed by high levels of total coliforms, fecal coliforms and fecal streptococci (Mezbour et al. 2018). Moreover, observations made during the sampling period showed that lakes are habitats to more aquatic/macrophytic plants, such as *Nelumbo nucifera, Pandanus helicopus, Eleocharis dulcis* and *Lepironia articulata*, than artificial lakes, which can provide habitat, food and refuge for crustaceans.

In order to enhance and to visualize the complex relationships of crustacean distributions in their biotope, the NMDS ordination technique of is the most reliable and it is known to be an indirect gradient analysis which creates an ordination based on a dissimilarity or distance. This revealed an overlap between the three communities, which is justified by the presence of common species; this result is supported by the Sørensen index, which reflected the level of similarity between crustacean's communities. These results; indicate that, despite the distance (56 km) separating the two Ramsar protected areas, Tonga Lake and Birds Lake, there is a high degree of connectivity at the functional level between the assemblages due to the large number of shared species and their functional traits. Furthermore, this reveals site specialization, as Birds Lake which is dominated by Copepods (*C. fuscus* 1427 and *Cyclops Sp* 790), El Kannar Lake which is dominated by Cladocerans (*S. expinosus* 2119) and Tonga Lake dominated by Ostracods (*Cypris sp* 266) and Decapods (*A. desmaresti* 141).

In our study, we identified 4 orders of crustaceans: Cladocerans, Copepods, Ostracods and Decapods. This means that the knowledge of the ecological characteristics and dynamics of the populations of these orders is essential. In general, Cladocerans are abundant filter feeders in various biotopes, in small and large freshwater, brackish or saltwater ponds, in the open waters of large lakes, in bottom sediments and among vegetation in the littoral zone of flowing waters of different types (Forró et al. 2008). Most Cladocerans may be bacterivorous, herbivorous or detritivorous, feeding on a wide range of elements, including organic detritus (Hayashi-Martins et al. 2017). The Cladoceran populations reach their abundance peak in the spring and autumn seasons, and when ecological conditions deteriorate, the males appear (Nandini and Sarma 2019). Cladocerans have the capacity to adapt to the environment, i.e. change their shape according to the season, dissolved oxygen, and the presence of fish. Their abundance can be associated with a close relationship with the dense presence of aquatic vegetation (Bolduc et al. 2016), as they are specialized in exploiting microenvironments provided by vegetation (Forró et al. 2008). In our work, Cladocerans' populations such as the Daphniidae family: *D. pulex*, *D. magna, Simocephalus expinosus* and *S. vetulus* are common in the investigated lakes. *Ceriodaphnia sp* and *Daphnia atkinsoni* are specific in El Kennar Lake. The Chydoridae family is presented by a single species, *Chydorus brevilabris* in El Kennar Lake, and the Moinidae family is presented by *M. micrura* in Bird's Lake. Furthermore, Bouzidi et al. (2010) revealed the presence of 4 species of *Ceriodaphnia dubia*, *Ceriodaphnia reticulata, Chydorus sp* and *Moina micrura*. This is in agreement with our results, except for the *Diaphanosoma brachyurum* species, which were absent during our study period. These species disappear during the period from July to October periods, probably due to the physicochemical parameters of the water, such as conductivity, salinity and habitat depth. Our results are in agreement with those of Touati. (2008) regarding the spatiotemporal distribution of the genera *Daphnia* and *Simocephalus* in the temporary pools of eastern Numidia (Annaba and El Kala). Conductivity, salinity and water depth are the physicochemical factors influencing the spatial distribution of *Daphnia* and *Simocephalus*. In previous studies, 36 species belonging to 18 genera and 7 families (Sididae, Daphniidae, Bosminidae, Chydoridae, Ilyocryptidae, Moinidae and Macrothricidae) have been identified in Algeria. In addition to the 70 species already known from Algeria, we have now updated the list of 81 Cladoceran taxa known from the country. Among the taxa observed, *Simocephalus vetulus* (O.F. Müller, 1776) is the most frequently encountered species, recorded in 35 different sites, followed by *Daphnia magna* Straus, found in 25 sampling sites (Ghaouaci et al. 2018). We also report the occurrence of *Tanymastigites ajjeri* in Algeria, providing an update on the geographical distribution of large branchiopods (Chergui et al. 2024). Thirty species of Cladocerans were identified and classified in the families of Sididae, Bosminidae, Chydoridae, Daphniidae, Moinidae and Macrothricidae in various habitats in Morocco (Aoujdad et al. 2014). Thirteen Cladoceran species have been recorded throughout Turkey, some for the first time in these localities. The genus *Ceriodaphnia* proved to be the most dominant group, followed by the genera *Daphnia, Macrothrix, Moina and Bosmina Simocephalus* (Kaya and Altindağ 2007). This proves that these species are able to acclimatize and adapt to their environment.

Copepods, the second order of crustaceans, are found in almost all freshwater habitats, from the largest ancient lakes to subterranean waters, from pools of glacial meltwater to hot springs, and from hypersaline lakes to phytotelmata. They are extremely abundant in freshwater and comprise a major component of most planktonic, benthic and groundwater communities, including semi-terrestrial situations such as damp moss and leaf litter in humid forests. The largest copepod family is the Cyclopidae which comprises over 800 species (Dussart and Defaye 2006), the great majority belonging to two freshwater subfamilies, Eucyclopinae and Cyclopinae. Based on the results obtained, the taxonomic richness of the

Copepods is demonstrated by the presence of three species: *Cyclops fuscus, Cyclops sp* and *Temora affinis*. In general, the faunal composition and temporal distribution of Copepods in Tonga, Birds and El Kannar lakes are similar to the results obtained by various researchers in African lakes (Mahmoudi et al. 2022) and on the Atlantic coast of Morocco (El Khalki and Moncef 2007). It is important to note that the predominance of this group is explained by their highly varied diet, which allows them to develop in environments where prey such as protozoa, larvae of other crustaceans and rotifers are available. Houmani et al. (2023) revealed that the *Cyclops fuscus* species is highly prevalent in El Chatt Lake in the El Tarf province, whereas *Temora affinis*, which belongs to the suborder Calanoides, is only reported in our study in Tonga Lake. Our results revealed that Copepod had low species diversity, with only 3 taxa found in the samples. Hamil et al. (2021) also found 3 taxa (*Arctodiaptomus salinus, Copidodiaptomus numidicus* and *Cyclops strenuus*) in the Ghrib Dam the northwestern of Algeria. According to Ghaouaci et al. (2017), the most abundant Copepod species in the provinces of Tébessa and Souk Ahras in northeastern Algeria is *Eucyclops leschermoutouae* (Alekseev and Defaye 2004). While the study of the diversity and distribution of zooplankton organisms in the Hassi Ben Abdallah lake in Ouargla, south-east Algeria, showed a total of 5 Copepod taxa: (*Eudiaptomus sp.* (Kiefer, 1932) *Calanus sp.* (Leach, 1819) *Acartia sp.* (Dana, 1846), *Cyclops sp.* (O. F. Müller, 1776) and *Bryocamptus sp.* (Claus, 1863) (Kebabsa et al. 2019). The analysis of available information on diaptomid copepods in Tunisian inland waters revealed a total of 10 diaptomid species belonging to 7 genera and 2 subfamilies. This biodiversity is therefore strongly linked to the diversity of inland waters that characterize the country (Marrone et al. 2023).

As for Ostracods, they are widely distributed in all types of aquatic habitat, fresh, brackish and salt water (Meisch 2000; Altınsaçlı et al. 2020). The efficient colonization of their habitat can be attributed to several factors, such as their different modes of reproduction (parthenogenetism, amphigonism or both) (Ozawa 2013) or their relatively high ecological tolerances to different environmental conditions (Martens and Savatenalinton 2011). Previous studies of Ostracods in Algeria Samraoui et al. (1998), who gave lists of species of Rotifers, Cladocerans, Copepods and 6 Ostracods from Numidia, in the north-east of the country. In the south-western Algerian Sahara (Tindouf), Karanovic and Pesce. (2000) described a new species, *Martenscypridopsis materia*, found in inland waters. The first in-depth research on Ostracods in Algeria was undertaken by Ghaouaci et al. (2015), (2017) who provided a recent list of non-marine Ostracod taxa. In our case, Ostracods (*Cypris sp*) are represented in negligible proportions compared to the other orders (5.16%) of the total fauna. It is probable that the main factors limiting the distribution of these species are the low content of ions in the water, as mentioned by Iglikowska and Namiotko (2012). This means that the distribution of ostracod species is closely linked to the physicochemical characteristics of the waters (Perçin-Paçal et al. 2017). Furthermore, the research conducted by Saoudi et al. (2018) on the aquatic macroinvertebrates of the El Mekhada marsh in northeastern Algeria has identified species of Ostracods belonging to the Cyprididae family. Similarly, this study indicates that the physicochemical parameters of freshwater show a higher abundance of taxa during the wet season compared with the dry season, which is consistent with our results. Seasonal changes in water quality also have a direct influence on Ostracod species diversity. Additionally, previous work by Külköylüoğlu et al. (2021), as well as Yavuzatmaca. (2020), presented evidence supporting the preference of these species for certain habitat conditions, particularly freshwater. Their tolerance is low, and they have optimum values, with relatively high abundance in November and December. Thus, winter offers more stable conditions compared with summer (Külköylüoğlu et al. 2022). Over the 2002–2012 period, one hundred and five sites in Tunisia, covering different climatic zones from the Mediterranean to the desert, were sampled. Indeed, based on previous investigations, 9 families (Candonidae, Cyprididae, Cytherideidae, Darwinulidae, Ilyocyprididae, Leptocytheridae, Limnocytheridae, Loxoconchidae and Paradoxostomatidae), 29 genera and at least 45 species of non-marine ostracods are currently known (Marrone et al. 2020). For some Ostracod species, clear distribution gradients associated with different climatic conditions have been observed (Marrone et al. 2020). In northeastern Italy (Friuli Venezia Giulia), 74 taxa from 30 genera belonging to 9 different families (Darwinulidae, Candonidae, Ilyocyprididae, Notodromadidae, Cyprididae, Limnocytheridae, Cytheridae, Leptocytheridae and Xestoleberidae) were identified. The most common species is *Cypria ophthalmica* (133 records), followed by *Cyclocypris ovum* (86 records), *C. laevis* (49 records), *Cypridopsis vidua* (40 records), and *Notodromas persica* (28 records) (Pieri et al. 2009). Until now, 145 non-marine ostracod species have been known from Turkey (Külköylüoğlu et al. 2015). There were a total of 1,787 individuals belonging to 31 species recorded in all the basins of Konya, Antalya and the western Mediterranean in Turkey. Some of these species are common to all the basins, while others are new, such as *Fabaeformiscandona fragilis*, which is new to all the basins. Nine species were found to be common to all in Konya, Antalya and West Mediterranean basins in Turkey (Yavuzatmaca 2019).

Decapods are represented by the species *A. desmarestii* (Millet, 1831), which belongs to the family Atyidae. It is a freshwater shrimp found in North Africa and Southern Europe. It is generally found in the Mediterranean region. In Algeria, Ameur et al. (2022) revealed the presence of this species in Oubeira and Tonga lakes and in the mouth of the Mafragh River on the coastal basin of El Battah in Annaba's Gulf. The works of Mabrouki et al. (2018) in Morocco and Dhaouadi et al. (2009) in Tunisia provided evidence of the presence of this species in the Mediterranean basin. The same family of freshwater shrimp is represented by the species *Atyoida serrata* according to the inventory of Valade (2003) in Mauritius. On the other hand, the work of Chevalier and Clavier. (2020) in French Guiana on 4 species of shrimp collected in the Haut

Courcibo area shows that all the species belong to the Palaemonidae family, with the absence of the Atyidae family. Another research conducted by Dhaouadi. (2003) identified a new southern limit for this shrimp in the El Haoureb dam in central Tunisia and at three other dams, Sidi Salem, Lebna and Sidi Saâd. The distance between these three reservoirs means that they belong to three distinct bioclimatic stages (Dhaouadi et al. 2004). The Decapod from Greece, Holthuis. (1961) reported the species from Lake Koronia as *A. desmarestii.* Recent sampling, covering a dense station network of the Greek freshwaters, revealed the presence of *A. desmarestii* in the western and northern part of the mainland (Anastasiadou et al. 2004). The information obtained shows that *A. desmarestii* has been found in many Portuguese watercourses, including reservoirs, rice fields, coastal lagoons and temporary streams. Despite the ecological relevance of this shrimp in aquatic communities, scientific information about its distribution in the country is still fragmentary and scattered (Fidalgo and Gerhardt 2002).

Physicochemical factors are the main drivers of crustacean community composition, diversity and spatiotemporal distribution. Temperature is a fundamental factor in climate; its variability affects evaporation and evapotranspiration and, consequently, the salinity level of the water. This parameter depends on the altitude and distance from the sea and also varies with the seasons (Kumar 2012). Seasonal precipitation is important because it allows us to assess the variation in precipitation and its trend according to the different seasons of the year. It is an ecologically important factor, not only for the functioning and distribution of limnic ecosystems (Ramade 2003). The annual precipitation of the Mediterranean area is expected to show a decrease of about 4% for every 1 °C increase in global temperature. This decrease is expected mainly in the summer season for the northern regions of the Mediterranean Basin and across all seasons in the central and southern regions (Ali et al. 2022).

Apart from the changes in climate conditions, another important aspect of global warming is the increase in the frequency and intensity of extreme weather events (Lazoglou et al. 2024).

Physicochemical factors spatially structure communities in aquatic environments (Allan et al. 2021) and contribute to the local and regional diversity of aquatic fauna and flora. For instance, at the regional scale, communities are influenced by factors such as dissolved oxygen, temperature and salinity, which usually vary from one aquatic habitat to another (Figueroa and De los Rios-Escalante 2021). Environmental factors also change in time, particularly in temperate regions (e.g., from one season to another), influencing the life cycle of aquatic organisms and determining their abundance and community composition across time (Smeti et al. 2019). In addition, anthropogenic factors tend to change the physicochemical characteristics of water, influencing the structure and diversity of aquatic organisms (Fergani and Arab 2013). Physical (temperature, lake size) and chemical (nutrients, metals, and chloride) parameters of freshwater ecosystems have significant effects on crustacean species composition. In our case, decapod species (*A. desmaresti*) are more abundant during the month with the highest rainfall. Conversely, low rainfall or low water levels would reduce oxygenation and, consequently, the metabolic rate of these organisms. Cladoceran (Ceriodaphnia, Daphnia, Simocephalus, Chydorus, Moina) populations reach peak abundance under optimal thermal conditions, typically between 18 and 22 °C, and in waters characterized by neutral to slightly alkaline pH, as recorded in Lake El Kennar. In contrast, copepods (Cyclops, Temora) exhibit a broader ecological tolerance, persisting at higher pH levels, up to 8.5. Ostracode (*Cypris sp*) their relatively high ecological tolerances to different environmental conditions, our results indicates that the physicochemical parameters of freshwater show a higher abundance of taxa during the month with the highest rainfall, which is consistent with Külköylüoğlu et al. (2021), as well as Yavuzatmaca. (2020). There is an urgent need for effective conservation and adaptive management strategies, including temperature regulation, control of nutrient pollution, and the preservation of habitat connectivity. Implementing such measures can help mitigate biodiversity loss in freshwater ecosystems and enhance their resilience to the impacts of ongoing climate change (Kasinathan et al. 2024). Understanding the seasonal changes in physicochemical factors is crucial to determine the factors that drive the abundance and composition of aquatic communities.

This means that crustaceans such as Ostracods, Cladocera, Copepods and Decapods are very sensitive to any type of climate change or to modifications in the physicochemical parameters of the environment in which they live. Any change in these factors can influence their distribution, abundance and growth process. This is proved by the problem of global warming and the record number of droughts that the world has experienced in recent years, according to the World Meteorological Organisation (WMO April 2021).

Conclusion

In this study, our observations underline that freshwater crustacean species diversity and distribution could be significantly correlated with environmental variables and climatic data related to their biotopes. We recorded 14 species which match 7 families: Daphniidae, Cyclopidae, Cyprididae, Atyidae, Chydoridae, Temoridae and Moinidae. Furthermore, NMDS analysis showed a spatial effect in the crustacean communities and highlight three species assemblages. We have also observed several species common to all three lakes, some are more abundant and others are rarely found or newly identified in Algeria. The taxonomic composition of crustacean communities, in Tonga, Birds and El Kennar lakes, react to variation in geographic gradients and are likely to be endangered due to habitat alterations such as increasing temperatures in Algeria and nutrient pollution.

Altogether, our results also emphasize that crustaceans' biodiversity and species identification are an essential contribution to a better understanding of crustacean communities threatened by climate change and anthropogenic activities. Integrating fauna's biological and ecotoxicological assessments is recommended to conserve wildlife and restore natural habitats, and to upgrade and to enhance public awareness toward the importance of freshwater biotopes. This study provides one of the few quantitative assessments of freshwater crustacean communities. It helps to fill the knowledge gap on aquatic biodiversity in Algeria. Future research should target unexplored regions (Saharan areas, high plateaus, temporary wetlands). Comparing data provides a valuable framework for understanding biogeographical dynamics and the impact of environmental changes on freshwater biodiversity.

Author Contributions

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Data analysis, Data interpretation: BAROUR Choukri, BALI Imene, BERGHICHE Hinda

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Conflicts of Interest

The authors declare no conflicts of interest.

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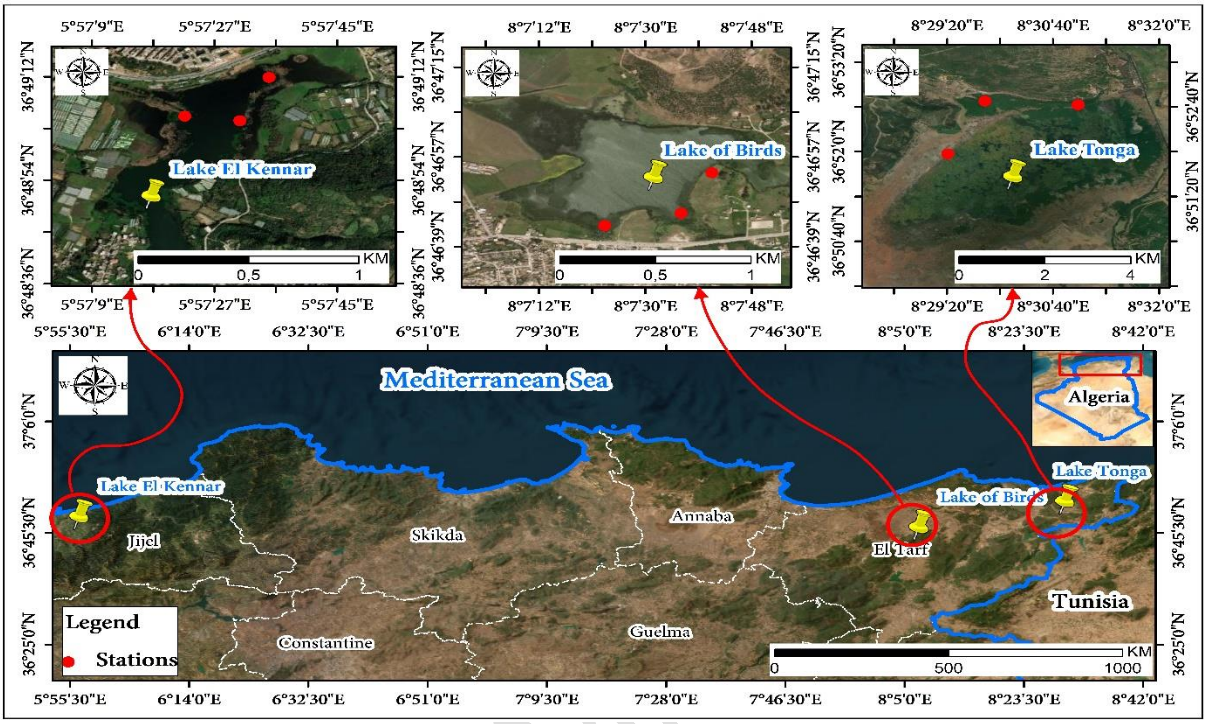


FIGURE 1. Crustacean sampling sites in two geographical regions of eastern Algeria: 1- Tonga Lake, 2- Birds Lake (El Tarf) and 3- El Kannar Lake (Jijel), Arcgis 10.4, (2025).

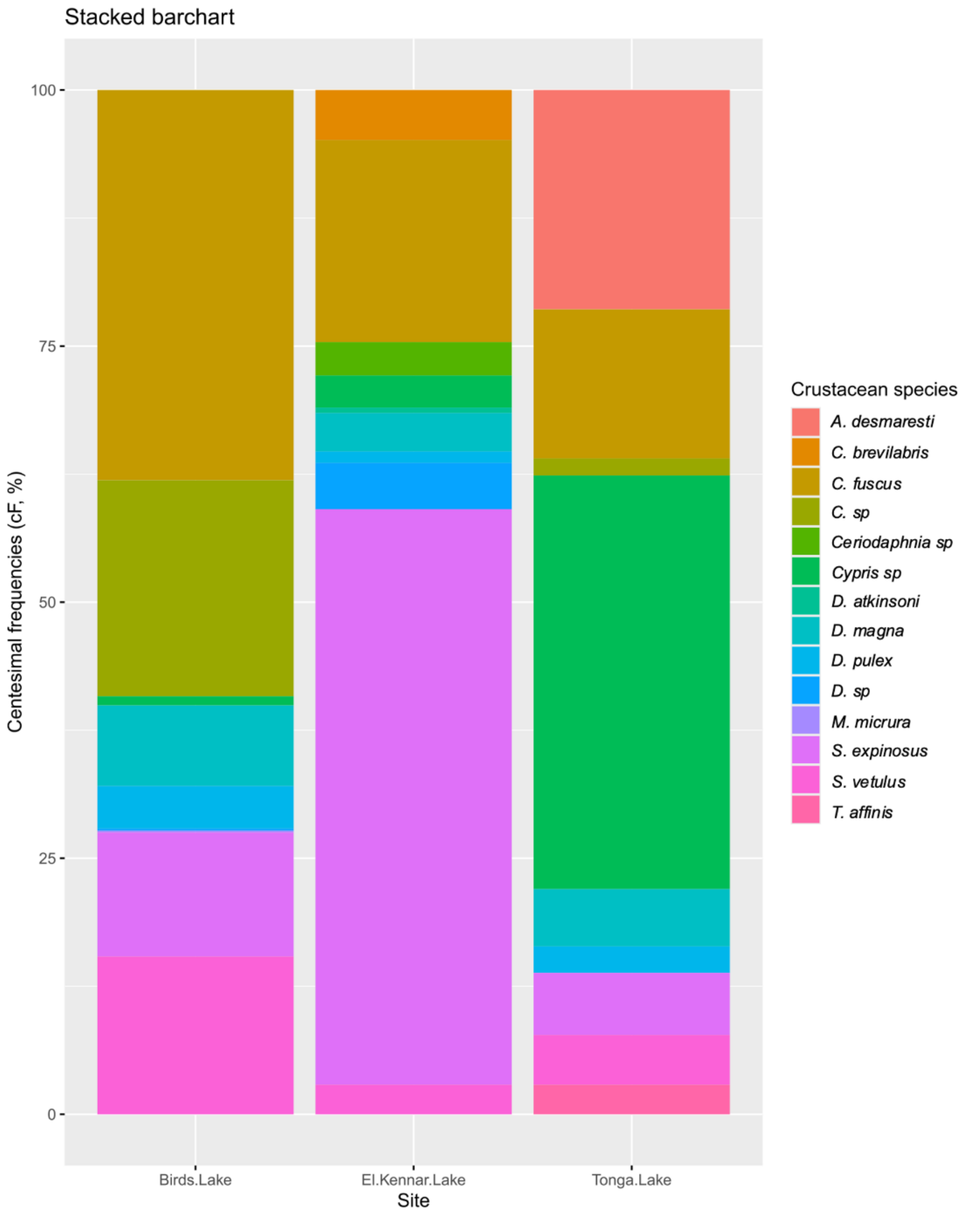
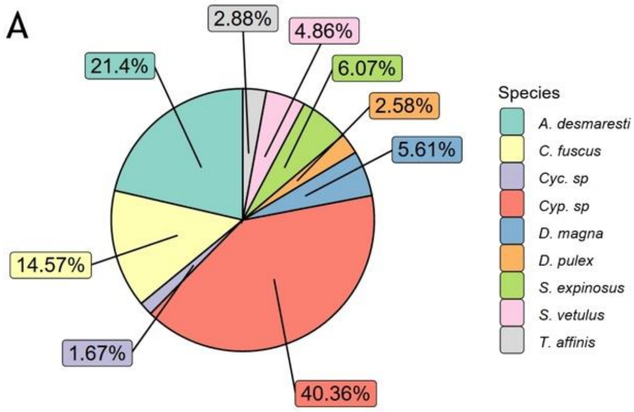
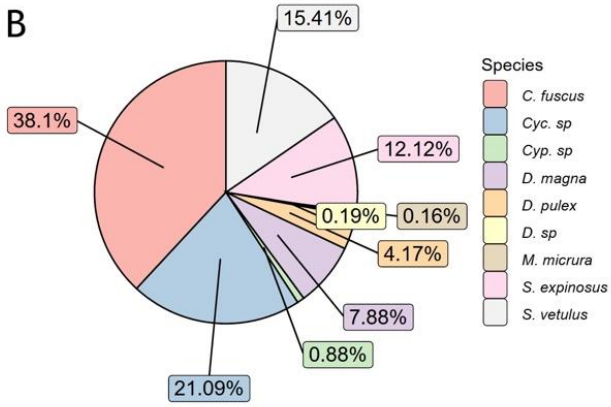


FIGURE 2. Species abundance stacked barchart showing the centisimal frequencies of different crustacean freshwater species recorded in Birds, El Kennar and Tonga lakes located in northeast of Algeria during the sampling period: May 2022-April 2023. Each color represents a different species and each bar represents a single site (*A*= 8175, *S*= 14).





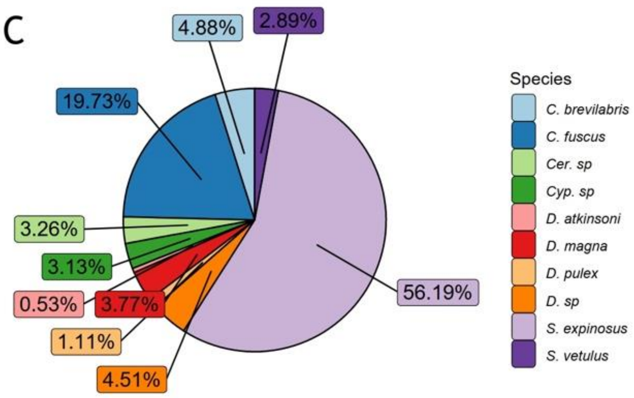


FIGURE 3. Pie charts representing the crustacean freshwater taxonomic composition in Tonga lake (A), Birds Lake (B) and El Kennar Lake (C) communities. The percentages and the taxonomic assignment are given at the species level during the sampling period: May 2022-April 2023 from three northeastern regions of Algeria. The recorded richness (S) in each biotope is respectively: 9, 9 and 10 species.

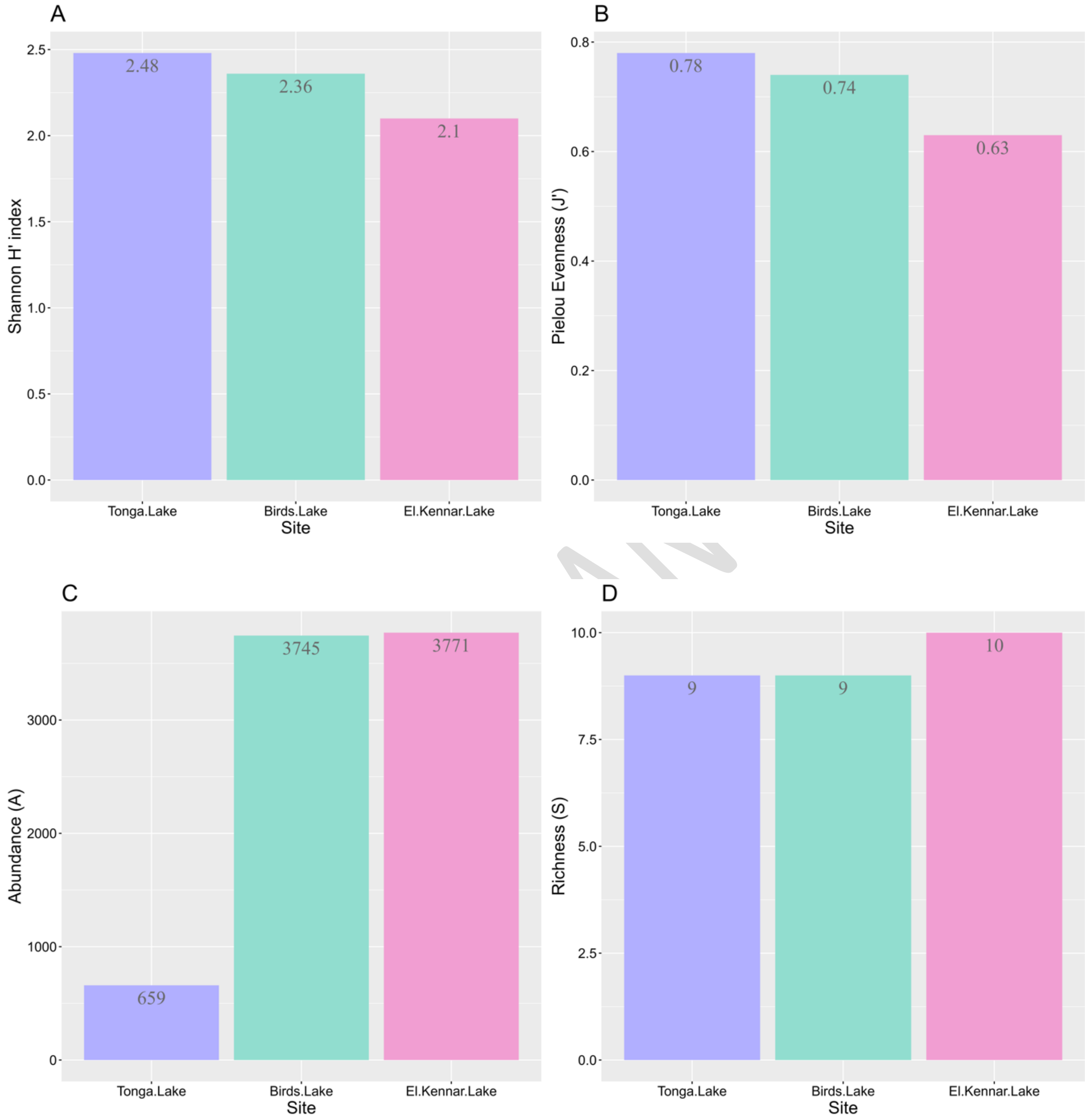


FIGURE 4. Diversity of the crustacean freshwater communities in Tonga, Birds and El Kennar lakes estimated at the α-diversity level during the sampling period: May 2022-April 2023 from three northeastern regions of Algeria. The barplots are expressing two ecological indexes (Shannon's diversity index, Pielou's evenness index) and two other ecological parameters (Abundance and Richness).

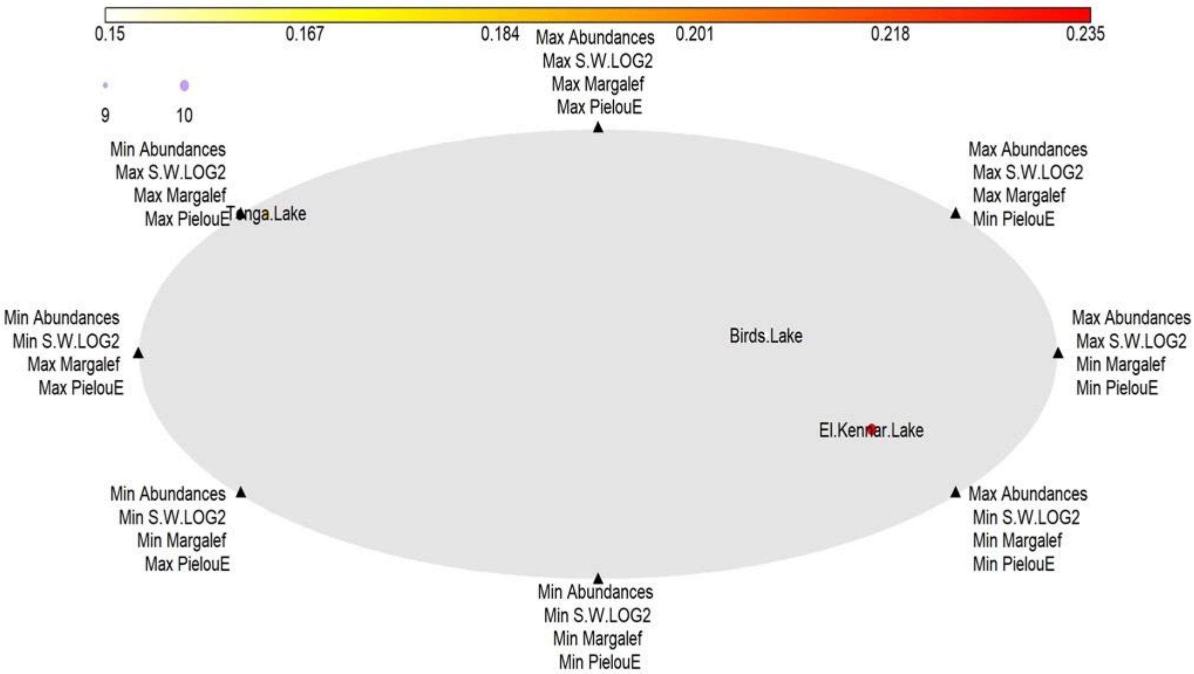


FIGURE 5. Differentiating assemblages of crustacean species on the basis of the DER algorithm (Gonzalez 2023) applied to abundances, Shannon's diversity index, Pièlou's evenness index and Margalef's index. Color gradient is the rarity Leroy index in each sample site. Bubble size scale is the species richness (S). The DER algorithm summarizes species diversity among all of freshwater crustacean samples collected from Tonga, Birds and El Kennar lakes in northeast Algeria during the sampling period: May 2022-April 2023.

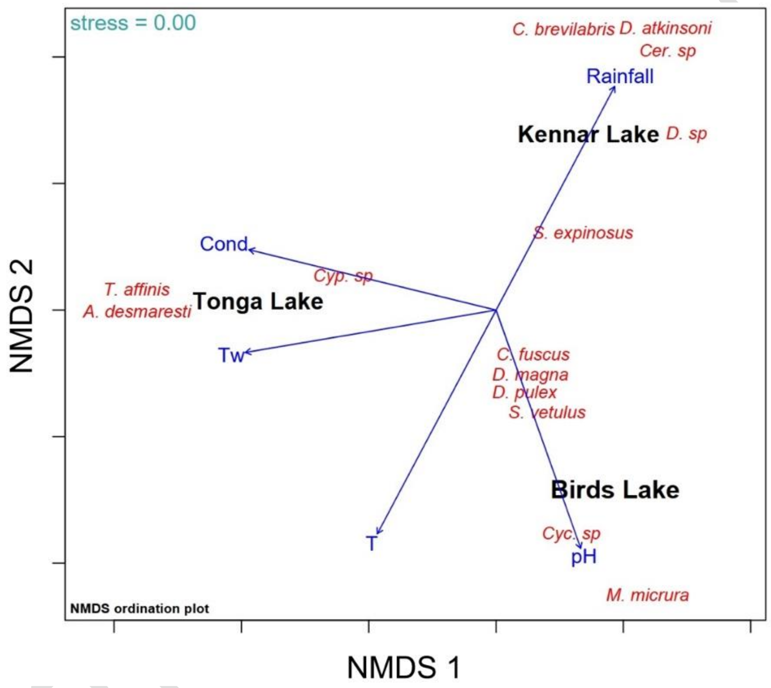
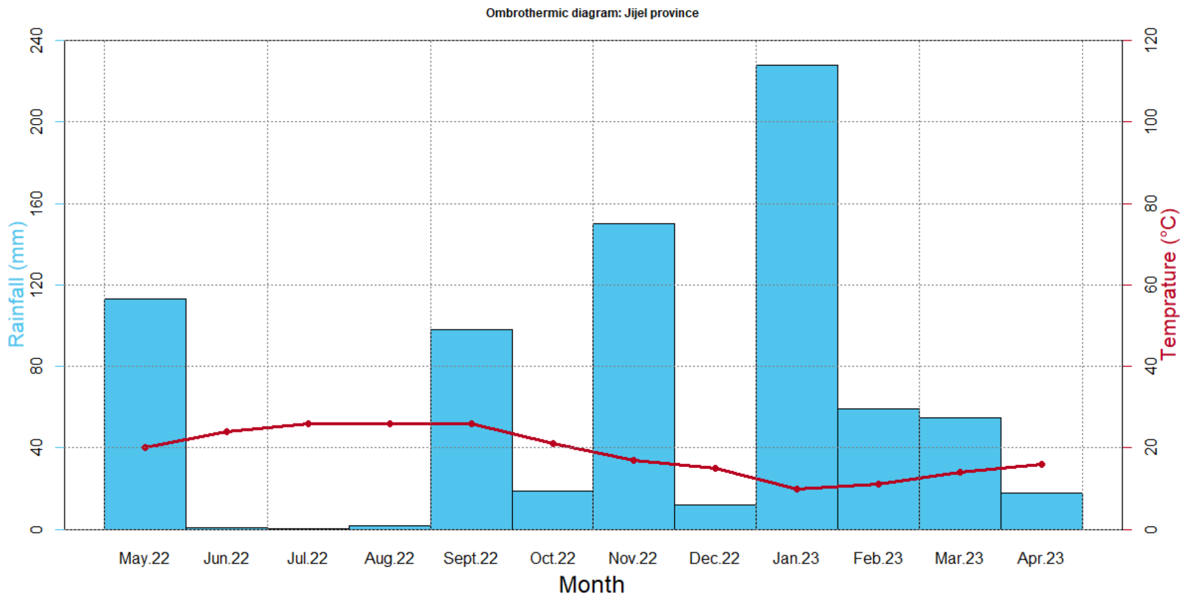


FIGURE 6. The non-metric multidimensional scaling (NMDS) of the freshwater crustacean communities' structure. The ordination plot is based on the Bray-Curtis dissimilarity matrix (stress value = 0.00). The ordination plot shows both the lakes (biotopes) and the crustacean species (*S*=14). The blue arrays present possible effects of measured environmental and climatic variables on species assemblages. The NMDS plot clearly shows a noteworthy level in β-diversity.



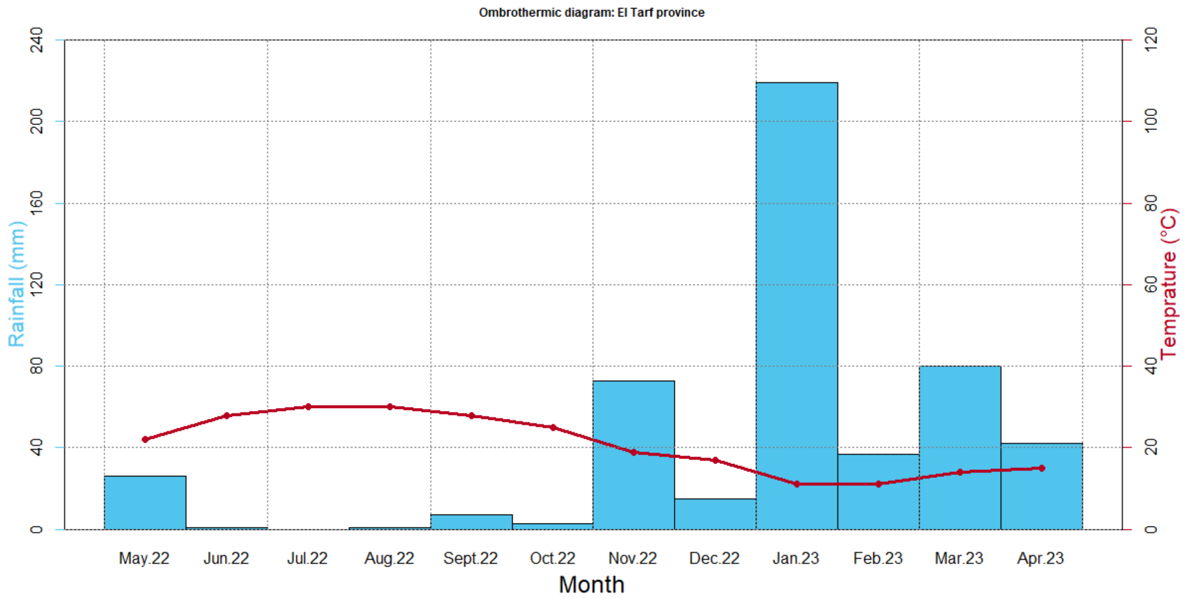


FIGURE 7. Ombrothermic diagram showing the monthly mean temperature (red line) and rainfall (bars) in both El Tarf and Jijel provinces, Algeria, from May 2022 to April 2023.

TABLE 1. Mean, standard deviation, minimal and maximal values of the environmental parameter measured in Tonga, Birds and El Kennar lakes from May 2022 to April 2023. For each parameter, the different letters indicate significant differences, according to Dunn's test, between lakes.

Site		Temperature (C°)	pH	Conductivity (µs/cm)
Tonga Lake	mean	23.38 ***a***	7.65 ***a***	1427 ***b***
	sd	2.70	0.68	188.74
	min	19.20	7.05	1100
	max	26.60	8.80	1598
Birds Lake	mean	22.07 ***a***	8.48 ***a***	648.33 ***a***
	sd	3.86	0.39	262.44
	min	17.90	8.00	400
	max	27.20	9.00	980
El Kennar Lake	mean	21.78 ***a***	7.56 ***a***	799.17 ***ab***
	sd	3.90	0.93	452.30
	min	17.70	6.66	414
	max	26.50	8.90	1600