

Impact of Leachates on the Structure of the Phytoplankton Population and the Water Quality in the Peri-Urban Stream Ntinetchoueh in a Mountainous Region (Bafoussam, West Cameroon)

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Abstract

Landfill leachates represent a major threat to freshwater ecosystems, particularly in rapidly urbanizing regions of Sub-Saharan Africa. This study investigated the effects of leachates from the Banefo landfill (HYSACAM) on the physicochemical characteristics and phytoplankton community structure of the Ntinetchoueh stream (Bafoussam, West Cameroon) over a seasonal cycle (April 2023 to February 2024). Five sampling stations were monitored, including sites exposed to leachate discharge. Water quality analysis revealed a relatively low temperature ($21.3^{\circ}\text{C} \pm 0.24^{\circ}\text{C}$), a slightly alkaline conditions ($\text{pH} 7.8 \pm 0.14$), and a moderate mineralization ($339.42 \pm 54.6 \mu\text{S}/\text{cm}$), coupled with elevated CO_2 ($14.55 \pm 6.35 \text{ mg}/\text{L}$) and nutrient concentrations, notably NH_4^+ ($0.8 \pm 0.32 \text{ mg}/\text{L}$) and orthophosphates ($0.88 \pm 0.22 \text{ mg}/\text{L}$), indicating substantial organic pollution. At the impacted station (S3), leachate inputs significantly increased conductivity and nitrogenous compounds while reducing Dissolved Oxygen (O_2) and pH. A total of 57 phytoplankton species were identified across four major classes, with Bacillariophyceae dominating community structure (79% of total density). *Synedra ulna* was the most abundant species, while *Oscillatoria* sp. and *Navicula cryptocephala* were the only regular species, whereas Bacillariaceae exhibited the highest taxonomic diversity. Species richness peaked upstream of contamination (S2), while maximum cell

densities were recorded during the dry season. The predominance of accessory taxa (70.17%) reflects high ecological sensitivity to environmental stress. Overall, leachate inputs drive nutrient enrichment and physicochemical alterations, leading to significant shifts in phytoplankton structure and a decline in aquatic biodiversity.

Keywords

Impact of Leachate, Phytoplankton, Water Quality, Ntinetchoueh, Bafoussam

1. Introduction

Urbanization and economic development lead to an increase in food needs and a rise in waste production per inhabitant [1]. The intensification of this urbanization, along with agricultural and industrial activities, is responsible for considerable production of solid and liquid waste that degrades water quality [2]. Moreover, water resources are dwindling, and their quality is deteriorating. According to several estimates, the significant increase in open-air deposits would be responsible for half of the current trends in environmental degradation, including water pollution [3]. The management of water bodies has therefore become one of the priority themes for multiple international organizations in terms of sustainable development [4]. The city of Bafoussam produces an average of 200 tons of Municipal Solid Waste (MSW) per day [5]. The relationship between waste management practices, water pollution, and public health often provides valuable insights to support sustainability in municipal solid waste (MSW) management and to influence the adoption of sustainable environmental and public health policies [6]. Most often, MSW discharges produce leachate that contains a variety of chemical contaminants that are extremely dangerous to water resources, aquatic species, and human health due to poor landfill management [7]. Phytoplankton are among the first aquatic organisms to respond to anthropogenic pressures, thus serving as one of the direct indicators of nutrient concentration in the water column [8]. With the aim of providing valuable information to support sustainability in MSW management and influence the adoption of environmental policies, this study aims to assess the impact of leachates on the physico-chemical quality of the water as well as on the phytoplankton community of the Ntinetchoueh River, which provides numerous ecosystem services to the local populations.

2. Materials and Methods

2.1. Presentation of Study Area

Bafoussam is located in the Western Highlands of Cameroon, covering an area of 2600 hectares, with a population of 495,735 inhabitants in 2025, between latitudes

5°26' and 5°31' North, and longitudes 10°21' and 10°30' East [9]. The climate of the region is characterized by a long rainy season of 8 to 9 months (April-October) and a short dry season of 3 to 4 months (November-March). Therefore, the city of Bafoussam is marked by abundant rainfall (1940 mm/year), and in quantitative terms, the water supply for the population should not present any difficulties. However, the qualitative aspect should not be underestimated [10]. This is partly caused by the urban waste produced and accumulated, which poses concerning environmental problems [5]. Moreover, the open municipal landfill exposes local residents and surrounding hydrosystems to major environmental issues.

2.2. Description of the Sampling Stations

During this study, 5 sampling points (Figure 1) located on both sides of the leachate entry point (Figure 2(A)) in the watercourse were chosen (Table 1).

Stations S1 (Figure 2(B)) and S2 (Figure 2(C)) were placed upstream of the leachate to serve as a reference in order to better understand the impact of the leachate on the other stations. On the other hand, S3 (Figure 2(D)) located approximately 0.81 km from the dump and positioned at the confluence between the watercourse and the leachate. It allowed the assessment of the direct impact of

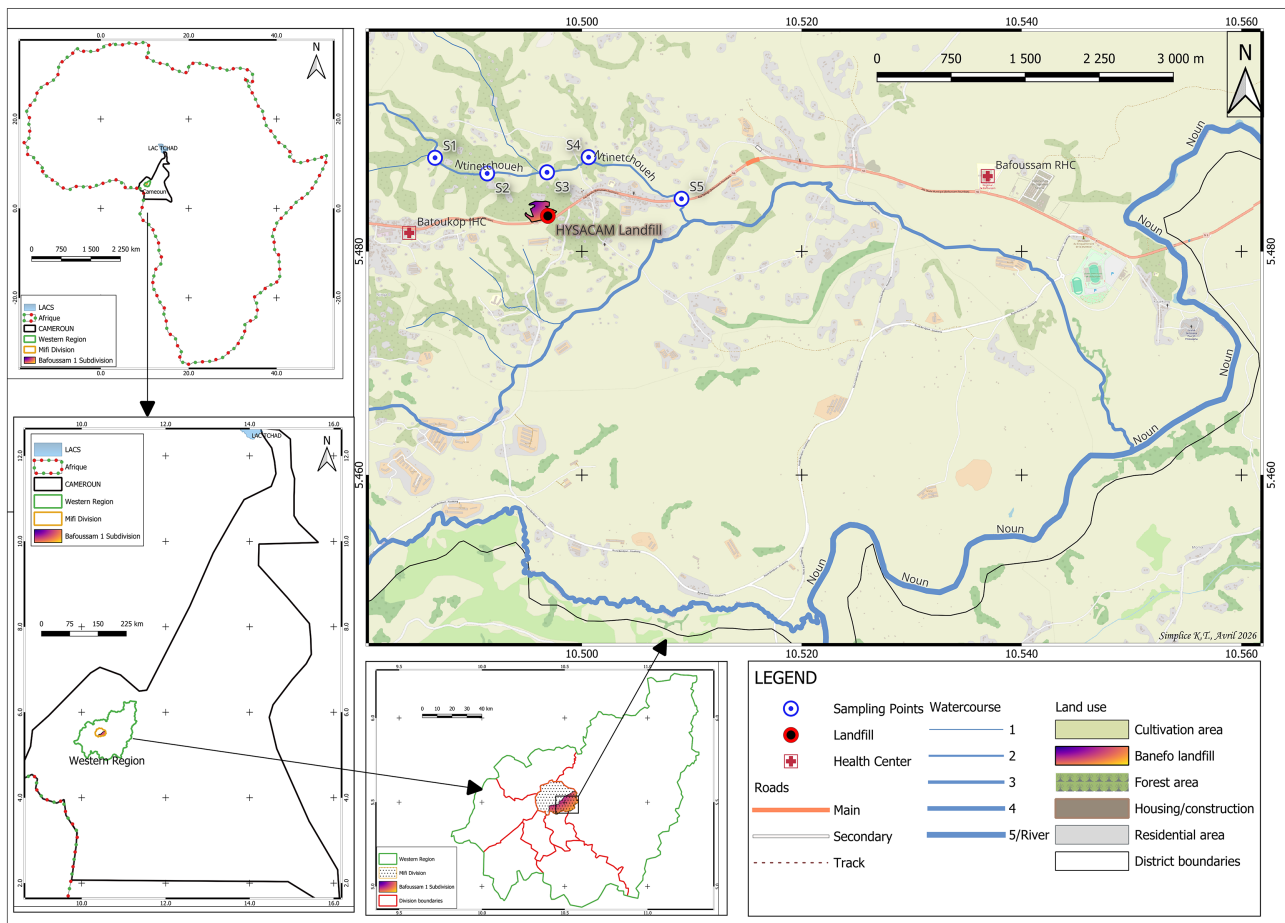


Figure 1. Geographical location of the sampling point in the studied stream (INC, 2024).

Leachate discharge



Figure 2. Partial views of the studied sampling points: Leachates (A), S1 (B), S2 (C), S3 (D), S4 (E), S5 (F).

Table 1. Geographical coordinates, morphometric characteristics and sources of pollution in Ntinetchoueh.

| Sampling stations | Pictures | GPS coordinates | | Morphometric characteristics (m) | Main activities and sources of pollution |
|-------------------|----------|---------------------------------|--------------|----------------------------------|--|
| | | Latitude (°N) Longitude (°E) | Altitude (m) | | |
| S1 | B | 05.48784836° 010.49112017° | 1049.39 | Depth: 0.80 Width: 1.20 | Farms |
| S2 | C | 5.48800955° 010.49368860° | 1048.94 | Depth: 0.70 Width: 1.50 | Farms |
| S3 | D | 05.484762433° 10.49777218° | 1043.26 | Depth: 0.72 Width: 1.90 | Farms and Leachate |
| S4 | E | 5.484791841° 10.49977730° | 1035.03 | Depth: 0.65 Width: 2.15 | Farms, leachate and lye |
| S5 | F | 05.48470476° 10.50906449° | 1031.16 | Depth: 0.90 Width: 2.20 | Farms, leachate, lye and sand removal |

leachate on the physicochemical properties of the water and the biodiversity of phytoplankton. Finally, S4 (**Figure 2(E)**) located 0.21 km from S3, and S5 (**Figure 2(F)**) located 1.38 km from S4, made it possible to assess the self-purification ca-

capacity of the stream and to determine the portion of the stream affected by this pollution. All these sampling points are characterized by a less human-impacted watershed, waters with a turbid appearance during the rainy season, and riparian vegetation dominated by *Tithonia diversifolia*. S4 and S5 are downstream stations characterized by mixed anthropogenic impacts rather than a single pollution source. Station S4 is influenced by a combination of agricultural activities (farms) and inputs from landfill leachate and lye, resulting in a composite pressure that integrates both nutrient enrichment and chemical contamination. Station S5 experiences an even more complex disturbance regime, with additional pressure from sand extraction activities alongside farms, leachate, and lye inputs. This combination of stressors suggests that observed physicochemical and biological alterations at these sites reflect cumulative and interacting impacts, rather than the sole influence of landfill-derived leachate.

2.3. Sampling and Measurement of Physico-Chemical and Biological Variables

2.3.1. Sampling

This study was conducted between April 2023 and February 2024, with sampling carried out in four campaigns: two during the rainy season (April and October) and two during the dry season (December and February). Samples for analysis were collected once a month during each campaign. These samples were collected directly from the surface down to a depth of approximately 0.5 m at the various stations using 250 ml and 1000 ml polyethylene bottles with double stoppers, filled to the brim without creating bubbles, then stored and transported in refrigerated containers for laboratory analysis. For phytoplankton, a 10-litre bucket was used, and the sample was filtered through a sieve with a mesh size of 34 μm and a diameter of 10 cm. The process was repeated three times until a filtered water volume of 30 litres was reached. The net was then rinsed with the sample water in the opposite direction to that of the filtration. The resulting retentate was then transferred into clean, transparent 500 ml glass bottles and fixed in situ with 2.5 ml of Lugol's solution.

2.3.2. Measurement of Parameters

- **Temperature**

Temperature is a key physical parameter that influences all biological and chemical processes in aquatic environments. In particular, it controls the solubility of oxygen, the rate of biochemical reactions and the metabolic activity of aquatic organisms. Sudden changes in temperature can cause significant ecological stress and alter the composition of biological communities [11].

- **Dissolved oxygen (DO)**

It plays a vital role in the functioning of hydrosystems; its presence in water is due partly to dissolution from the atmosphere, but also to the process of photosynthesis by aquatic vegetation [12].

- **pH and dissolved CO₂ (carbon dioxide)**

pH is a key parameter in assessing water quality, as it determines whether the

water is acidic or alkaline. It directly influences the availability of nutrients and the toxicity of certain chemical elements. A pH outside the range of 6.5 - 8.5 can have adverse effects on aquatic organisms [13].

As for the dissolved CO₂ content, it was measured in two stages:

- In the field, the CO₂ was determined by adding the raw water sample to a 200 ml volumetric flask—which had previously been filled with 20 ml of 20 N NaOH and 2 to 3 drops of phenolphthalein—until the mark was reached. The resulting pink-coloured mixture was stored in a 250 ml double-stoppered polyethylene bottle.
- In the laboratory, 50 ml of this sample was titrated with 10 N HCl until complete decolourisation. The CO₂ content of the water, expressed in mg/L, was then determined using the formula: CO₂ (mg/L) = (blank – burette drop) × 17.6.

- **Electrical conductivity**

Electrical conductivity (EC) reflects the concentration of dissolved ions in water. High values generally indicate high mineralisation or pollution of anthropogenic origin. There is a positive correlation between conductivity, TDS and urban or industrial pollution of surface waters [14].

Dissolved oxygen was measured in situ using a HANNA HI 9146 oximeter, whilst temperature, pH and electrical conductivity were measured using a LAQUA HORIBA PC 220 multi-parameter analyser.

- **Nutrients: nitrates and phosphates**

Nitrates and phosphates are essential nutrients, but excessive levels in natural waters lead to eutrophication. This process causes excessive algal blooms and a reduction in dissolved oxygen, thereby affecting aquatic biodiversity. High nutrient concentrations are directly linked to domestic and agricultural discharges and landfill leachate [15]. Ammoniacal nitrogen can be used as a pollution indicator, as its levels are high in polluted waters [16].

- **Orthophosphates**

In rivers, phosphorus generally occurs in dissolved (organic and inorganic) or particulate form. Phosphorus is naturally present in certain igneous or sedimentary rocks. Its leaching through natural erosion processes leads to its solubilisation in aquatic environments. Water colour and nutrient content (ammoniacal nitrogen and orthophosphates) were analysed in the laboratory using a HACH DR/3900 spectrophotometer, in accordance with standard techniques and the recommendations of Rodier [17].

- **Oxidability**

Oxidability refers to an estimate of the concentration of organic matter in low-load waters [18] [19]. This variable measures the amount of oxygen required to reduce potassium permanganate (KMnO₄) by the organic matter present in water [19]. The oxidised molecules are primarily organic molecules, but inorganic molecules may also be oxidised. Surface waters typically have oxidabilities ranging between 3 and 8 mg/L of oxygen [17]. It was measured by volumetric analysis. In a 500 ml Erlenmeyer flask, 200 ml of raw water sample was added, followed by 2 ml of monosodium carbonate, and the mixture was brought to the boil. As soon

as boiling began, 20 ml of KMnO_4 N/80 was added. Ten minutes after boiling began, the Erlenmeyer flask was cooled under running water, then 5 ml of 25% H_2O_4 and 20 ml of Mohr's salt were added. The decoloured sample was then titrated with KMnO_4 N/80 until a pink colour appeared. The blank was prepared under the same conditions as the sample, but replacing the sample with distilled water. The oxidisability, expressed in mg/L of O_2 , is obtained using the formula:

$$\text{Oxidability (mg}\cdot\text{L}^{-1}) = [(\text{Sample burette discharge} - \text{Lowering of the control burette})/2] \times 3.95 \quad (1)$$

- **Phytoplankton**

In the laboratory, the sample was left to settle for 48 hours, after which the supernatant was siphoned off to obtain a dense sediment rich in seston. Qualitative (diversity) and quantitative (density) analyses were then carried out to identify and count the cells using an OLYMPUS CK2 microscope at 400× magnification, in accordance with the methodology proposed by Utermöhl [20]. Densities, meanwhile, were calculated using the following formula:

$$D = N_i \times S \times 1000 / (v \times s) \quad (2)$$

where: D = Density (ind./L);

S = area of the counting chamber (100 mm²);

N_i = number of individuals counted for the species i ;

s = total area of the counted field;

v = volume of sediment sample (10 mL);

1000 = conversion factor.

2.4. Data Analysis

The collected data were analyzed using Microsoft Excel 2016, SPSS 26.0, and GraphPad Prism 8.0.2. Kruskal-Wallis and Mann-Whitney tests were applied to the obtained data to assess significant differences between the values of the analyzed variables. The calculated frequency of occurrence (F) allowed the classification of taxa into five categories according to Dufrene and Legendre [21]: F = 100%: Omnipresent species (*****); 75% ≤ F < 100%: regular species (****); 50% ≤ F < 75%: constant species (**); 25% ≤ F < 50%: accessory species (**); F < 25%: rare species (*). The Shannon-Weaver and Pielou indices were used to determine the structure and dynamics of the phytoplankton community. Spearman correlations were used to determine the influence of environmental variables on phytoplankton taxa.

3. Results

3.1. Physico-Chemical Variables

During this study, the results of water temperature measurements showed values ranging from 19.4°C (S5 – April) to 22.7°C (S2 – February) with an overall average of 21.3°C ± 0.24°C (Figure 3(A)). Kruskal-Wallis and Mann-Whitney U tests showed a significant variation of the data between the studied stations ($p < 0.01^{**}$)

in contrast to the non-significant variation observed between months ($p > 0.05$). Regarding dissolved oxygen, the obtained values clearly show a critical decrease at S3 during the months of October (2.2%), December (2.3%), and February (29%) (**Figure 3(B)**). The data for this parameter varied significantly between different months but not significantly between stations. Unlike dissolved CO₂, the analysis results showed very high CO₂ production at S3 during the month of heavy leachate runoff (October) as well as in December during the dry season (**Figure 3(C)**). Overall, CO₂ fluctuated between 0 mg/L (S1 & S2 – February) and 44 mg/L (S3 – October) with an average of 14.55 ± 6.35 mg/L of CO₂. There is no significant difference between the stations ($p > 0.05^*$) in contrast to the months ($p < 0.01^{**}$). As for the pH, the values obtained show a decrease in the water pH following the entry of leachate into the watercourse (S3) specifically in October. Overall, it varied between 7.11 UC at the station (S3 – April) and 8.51 UC at (S1 – February) with an overall average of 7.8 ± 0.14 UC (**Figure 3(D)**). This pH only varied significantly between the different months studied ($p < 0.01^{**}$). The electrical conductivity values, assessed in this study to determine the mineralizing activity in the studied watercourse, showed intense mineralizing activity at S3 starting from October. Conductivity values fluctuated in this station from October between 1445 and 1248 $\mu\text{S}/\text{cm}$ (**Figure 3(E)**). Significant differences were observed only between the stations ($p < 0.05^*$).

Regarding the physico-chemical parameters indicative of organic pollution, the ammonium nitrogen (NH_4^+) levels fluctuated between 0.15 mg/L of NH_4^+ (S1 & S3 – April) and 2.16 mg/L of NH_4^+ (S3 – February) (dry season), with an overall average of 0.8 ± 0.32 mg/L of NH_4^+ , showing an increase in NH_4^+ concentration throughout the stream in October. However, this concentration is more pronounced at S3 in February (**Figure 3(F)**). Significant differences ($p < 0.01^{**}$) were noted only over time.

For orthophosphate (PO_4^{3-}) levels, the results obtained generally show a remarkable concentration of this element in the water starting from S3 and throughout all the months studied. These levels ranged from 0.082 mg/L of PO_4^{3-} (S2 – April) to 2.093 mg/L of PO_4^{3-} (S5 – October), with an average of 0.88 ± 0.22 mg/L of PO_4^{3-} (**Figure 3(G)**). Significant variations ($p < 0.05^*$) were observed both between stations and between months. No significant variation in the data was recorded during the study. The results of the analyses of biodegradable and non-biodegradable organic matter (Oxydability) in the water also showed a sharp increase in levels starting in October. These were more notable at stations S3 (221 mg/L of O₂) and S4 (243.91 mg/L of O₂), with peaks observed in December (**Figure 3(H)**).

The statistical analyses revealed significant spatial differences among sampling stations for several key water quality parameters. One-tailed *t*-tests showed significantly higher values of electrical conductivity, ammonium (NH_4^+), and orthophosphate (PO_4^{3-}) concentrations at impacted stations, particularly S3, compared to upstream stations S1 and S2 ($p < 0.05$). Post-hoc comparisons Tukey HSD [22] con-

firming that S3 differed significantly from S1 and S2 for most variables, while downstream stations S4 and S5 exhibited intermediate values, suggesting partial recovery along the Ntientchoueh. Temporal analysis also indicated significant differences between sampling periods. Notably, nutrient concentrations and conductivity were significantly higher during the rainy season (October), likely due to increased runoff, whereas some parameters such as ammonium peaked during the dry season (February), reflecting concentration effects under reduced flow conditions.

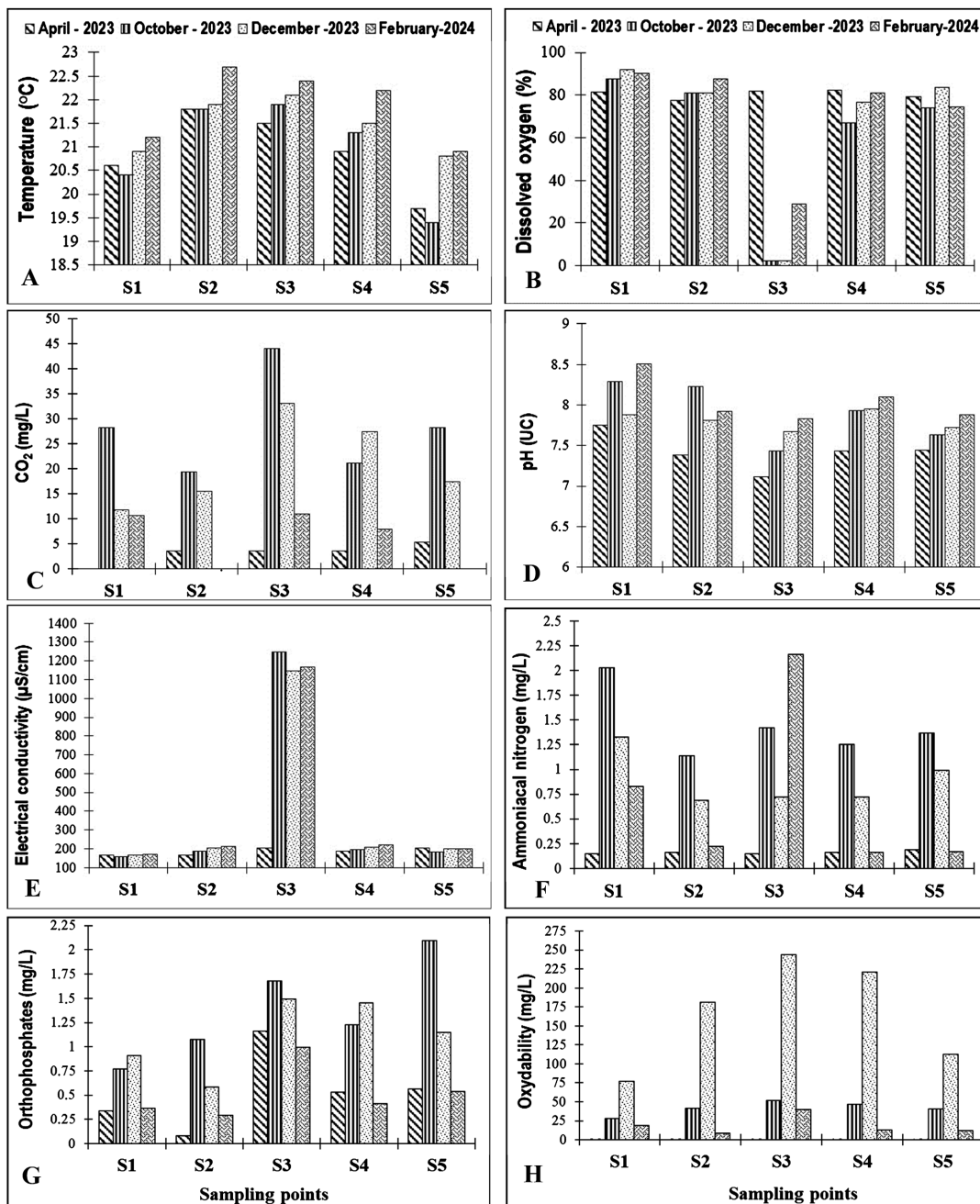


Figure 3. Spatio-temporal variations of temperature (A), Dissolved oxygen (B), CO₂ (C), pH (D), conductivity (E), NH₄⁺ (F), PO₄³⁻ (G), Oxydability (H).

3.2. Biological Characteristics

3.2.1. Taxonomic Richness and Overall Phytoplankton Density

The analysis of the phytoplankton population reveals a low diversity with 57 species belonging to 4 Classes, including Chlorophyceae, Cyanophyceae, Diatoms, and Euglenophyceae, 11 Orders, and 20 phytoplankton Families. The Class of Diatoms was predominant with 12 Families and 35 Species (**Table 2**). In terms of density, during this study, the Diatom class accounted for 79% of the total density. It was followed by Chlorophyceae and Cyanophyceae with 11% and 8% of the total density, respectively; Euglenophyceae were represented by only 2% of this density (**Table 2**).

Table 2. Diversity and overall density of phytoplankton identified during the study.

| Classes | Diversity (Number of Orders, Families and Species) | | | Density |
|----------------|--|----------|---------|---------|
| | Orders | Families | Species | (%) |
| Bacillariaceae | 7 | 12 | 35 | 79 |
| Cyanophyceae | 3 | 3 | 7 | 11 |
| Euglenophyceae | 1 | 2 | 7 | 02 |
| Chlorophyceae | 3 | 3 | 7 | 08 |
| Total | 14 | 20 | 56 | 100% |

Among the 12 families identified in this study, the Bacillariaceae family with 10 species and the Naviculaceae Family with 6 species, belonging to the Diatoms, were the most diverse. They were followed by the Closteriaceae Family (5 species) belonging to the Chlorophyceae and the Oscillatoriaceae and Euglenaceae Families, belonging respectively to the Cyanophyceae and Euglenophyceae, with 4 species each (**Figure 4**).

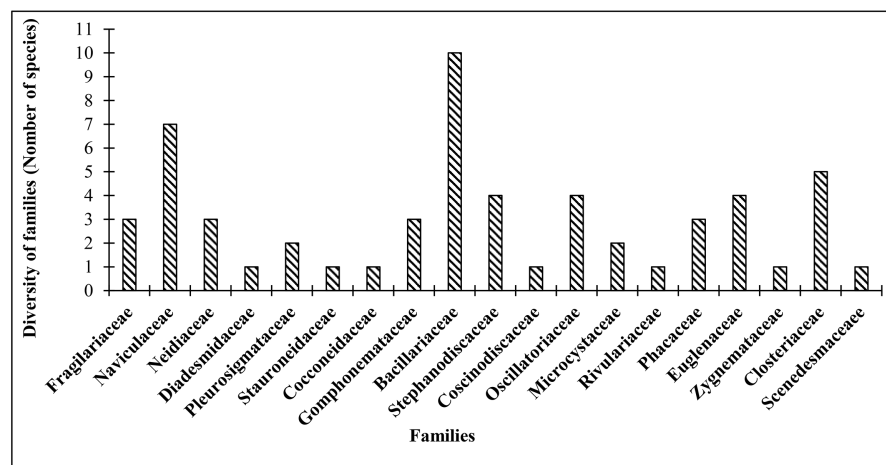


Figure 4. Species richness of phytoplankton families identified during this study.

3.2.2. Spatio-Temporal Dynamics of Phytoplankton Taxonomic Richness

Temporally, the month of April showed the greatest diversity with 39 species, while the month of December exhibited the lowest species richness with only 10 species (Figure 5(A)). Spatially, sampling points S1 and S2 were the most diverse with 28 and 30 species, respectively. This diversity decreases to 20 species at sampling points S3 and S4, then slightly increases again to 23 species at sampling point S5 (Figure 5(B)). The one-tailed *t*-test shows significant differences ($p < 0.01^{**}$) in species richness on both axes.

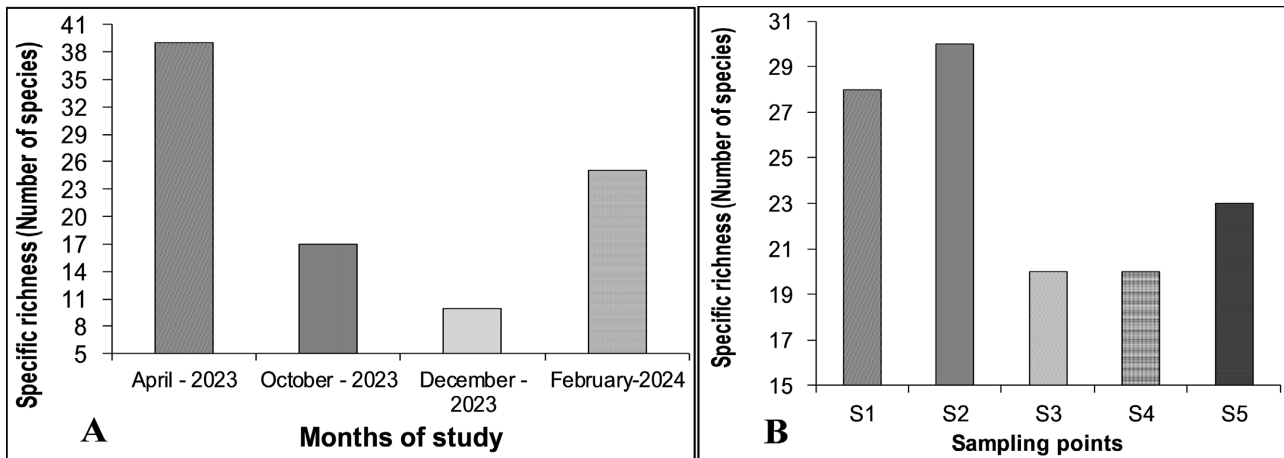


Figure 5. Temporal (A) and Spatial (B) variations of algal species richness during the study.

3.2.3. Temporal and Spatial Dynamics of Identified Phytoplankton Density

The temporal and spatial dynamics of phytoplankton densities during this study showed variations between the months of the study and the sampling stations. In terms of time, the highest phytoplankton density was recorded in February with 12.6 ind./L, whereas October, a period of heavy rainfall in the region, showed the lowest density with 4.13 ind./L (Figure 6(A)). In terms of spatial distribution, however, the highest density was recorded at sampling point S2 with 10.47 ind./L, while sampling point S3 had the lowest density with 5.27 ind./L (Figure 6(B)). The one-tailed *t*-test shows significant differences in phytoplankton densities between the studied stations ($p < 0.01^{**}$) and between the different sampling periods ($p < 0.05^*$). Significant spatial differences were observed, with station S3 showing lower diversity and altered phytoplankton densities compared to S1 and S2 ($p < 0.05^*$). Post-hoc tests confirmed that S3 differed significantly from upstream stations, while S4 and S5 displayed intermediate conditions. Temporally, diversity decreased during the rainy season, whereas higher densities were recorded during the dry season.

3.2.4. Frequency of Phytoplankton Occurrence

During this study, *Synedra ulna* was the only omnipresent species, while *Oscillatoria* sp. and *Navicula cryptocephala* were the only regular species. In addition, 13 taxa were consistently observed, namely, *Navicula* sp., *Caloneis* sp., *Diademis*

contenta, *Gomphonema olivacium*, *Nitzschia intermedia*, *Oscillatoria limnetica*, *Phacus orbicularis*, *Phacus succicus*, *Colacium cyclopicola*, *Spirogyra* sp., *Closterium lanceolatum*, *Closterium* sp., *Clostorium aciculare*. The other 40 taxa were accessory (Table 3). Furthermore, spatially, the analysis of occurrence frequencies at each sampling station (Figure 6) shows an absence of rare taxa but a dominance of accessory taxa, whose percentage varies between stations from 64% to 80% of the total species richness. These are followed, respectively, by constant taxa (15% - 32%), regular taxa, and ubiquitous taxa throughout the study (Figure 7).

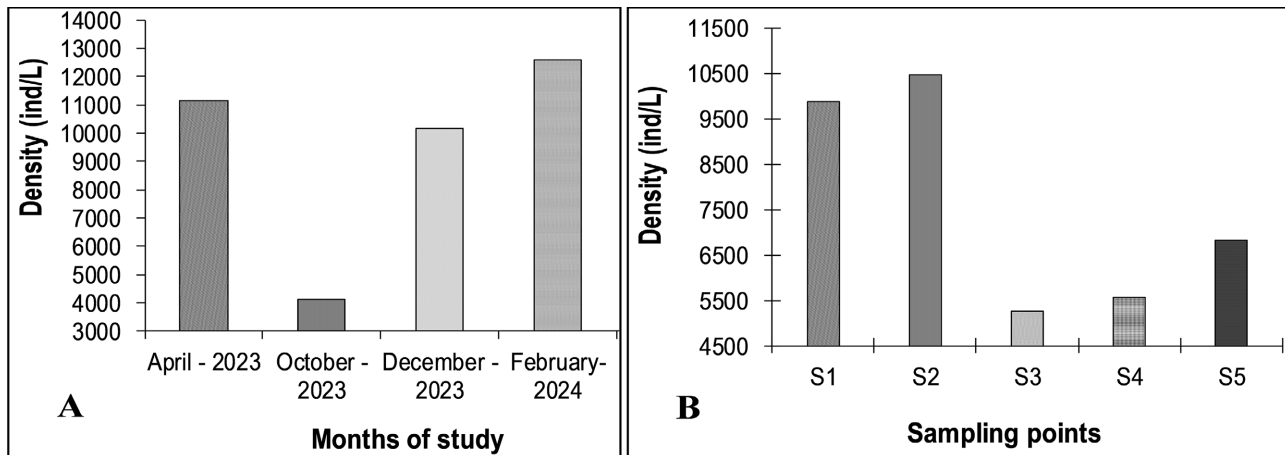


Figure 6. Temporal (A) and Spatial (B) dynamics of phytoplankton densities observed during the study.

Table 3. List and occurrence of the different phytoplankton taxa collected at the various stations during the study.

| Species | Sampling points | | | | |
|--------------------------------|-----------------|-----|----|-----|-----|
| | S1 | S2 | S3 | S4 | S5 |
| <i>Achnanthis lanceolaum</i> | 0 | ** | 0 | 0 | 0 |
| <i>Bacillaria</i> sp. | 0 | 0 | ** | 0 | 0 |
| <i>Caloneis</i> sp. | *** | ** | ** | *** | 0 |
| <i>Closterium abruptum</i> | ** | 0 | 0 | 0 | 0 |
| <i>Closterium lanceolatum</i> | 0 | 0 | 0 | 0 | *** |
| <i>Closterium moniferum</i> | ** | ** | 0 | ** | 0 |
| <i>Closterium</i> sp. | 0 | *** | 0 | 0 | 0 |
| <i>Clostorium aciculare</i> | ** | *** | ** | 0 | ** |
| <i>Cocconeis placentula</i> | 0 | ** | 0 | 0 | 0 |
| <i>Colacium cyclopicola</i> | *** | 0 | ** | ** | ** |
| <i>Coscinodiscus</i> sp. | 0 | 0 | 0 | 0 | ** |
| <i>Cyclotella meneghiniana</i> | 0 | 0 | 0 | ** | 0 |
| <i>Cyclotella</i> sp. | 0 | 0 | ** | 0 | ** |

Continued

| | | | | | |
|----------------------------------|-----|------|-----|-----|------|
| <i>Cymbella ventricosa</i> | ** | ** | 0 | ** | ** |
| <i>Denticula thermalis</i> | ** | 0 | 0 | ** | 0 |
| <i>Diademis contenta</i> | 0 | ** | 0 | 0 | *** |
| <i>Euglena viridis</i> | 0 | 0 | 0 | 0 | ** |
| <i>Girosigma acuminatum</i> | ** | 0 | 0 | 0 | 0 |
| <i>Gomphonema gracile</i> | 0 | ** | 0 | 0 | 0 |
| <i>Gomphonema olivacium</i> | *** | ** | 0 | 0 | ** |
| <i>Gomphonema sp</i> | ** | 0 | 0 | 0 | 0 |
| <i>Leponcinclis ovum</i> | 0 | 0 | ** | 0 | 0 |
| <i>Lyngbya sp.</i> | ** | ** | 0 | 0 | 0 |
| <i>Microcystis sp.</i> | 0 | ** | ** | 0 | 0 |
| <i>Navicula cryptocephala</i> | *** | *** | 0 | *** | **** |
| <i>Navicula pavillardii</i> | ** | 0 | ** | 0 | 0 |
| <i>Navicula sp</i> | ** | *** | *** | ** | ** |
| <i>Navicular bacillum</i> | 0 | 0 | ** | ** | ** |
| <i>Navicular pymaea</i> | 0 | ** | ** | 0 | 0 |
| <i>Navicular spp.</i> | ** | 0 | 0 | 0 | 0 |
| <i>Neidium claussi</i> | 0 | ** | 0 | 0 | 0 |
| <i>Neidium dissipata</i> | 0 | ** | 0 | 0 | 0 |
| <i>Neidium sp.</i> | 0 | ** | 0 | 0 | 0 |
| <i>Nitzschia amphibia</i> | ** | ** | ** | 0 | 0 |
| <i>Nitzschia intermedia</i> | 0 | ** | *** | 0 | 0 |
| <i>Nitzschia sp.</i> | ** | 0 | ** | 0 | ** |
| <i>Oscillatoria limnetica</i> | *** | *** | ** | ** | 0 |
| <i>Oscillatoria platensis</i> | ** | ** | 0 | 0 | 0 |
| <i>Oscillatoria sp.</i> | *** | **** | *** | *** | **** |
| <i>Phacus orbicularis</i> | *** | 0 | 0 | 0 | 0 |
| <i>Phacus succicus</i> | 0 | ** | 0 | ** | *** |
| <i>Planktothrix agardhii</i> | 0 | ** | 0 | 0 | 0 |
| <i>Pleurosigma sp.</i> | 0 | 0 | 0 | 0 | ** |
| <i>Pseudo-nitzschia sp.</i> | 0 | 0 | ** | ** | 0 |
| <i>Raphidiopsis mediterranea</i> | ** | 0 | 0 | ** | ** |

Continued

| | | | | | |
|----------------------------------|------|------|------|------|------|
| <i>Rhizosolenia</i> sp. | 0 | 0 | 0 | ** | ** |
| <i>Scenedesmus actiformis</i> | 0 | ** | 0 | 0 | 0 |
| <i>Spirogyra</i> | *** | 0 | 0 | ** | 0 |
| <i>Stauroneis phoenicenteron</i> | 0 | 0 | 0 | 0 | ** |
| <i>Stephanodiscus aestraea</i> | ** | 0 | 0 | 0 | 0 |
| <i>Strombomonas verrucosa</i> | 0 | 0 | 0 | 0 | ** |
| <i>Surrirella capronii</i> | ** | ** | 0 | ** | ** |
| <i>Surrirella linearis</i> | 0 | 0 | ** | 0 | 0 |
| <i>Synedra</i> sp. | *** | **** | ** | *** | *** |
| <i>Synedra ulna</i> | **** | **** | **** | **** | **** |
| <i>Trachelomonas</i> sp. | 0 | ** | 0 | 0 | 0 |
| <i>Ulnaria</i> sp. | ** | 0 | 0 | ** | 0 |

Legend: (**) = Accessories species; (***) = Constants species; (****) = Regular species; (*****) = Omnipresent species.

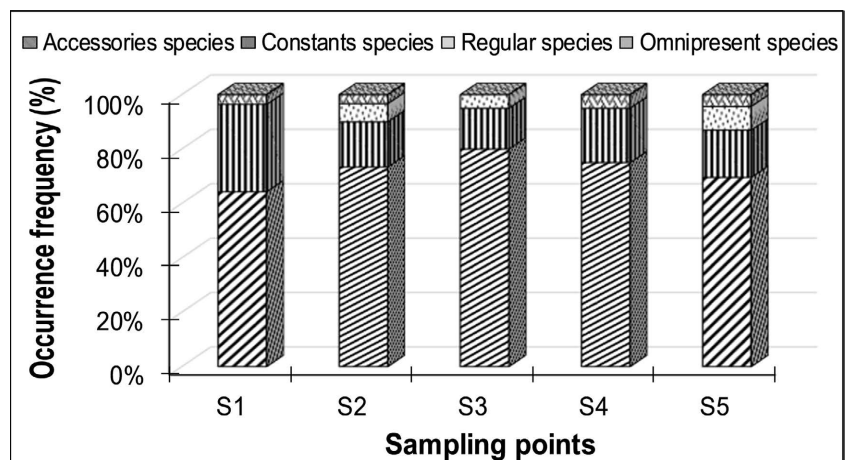


Figure 7. Frequency of occurrence of phytoplankton species in study sampling points.

3.2.5. Shannon and Weaver Diversity Index (H') and Pielou's Evenness

The Shannon and Weaver index values obtained at the temporal scale show a decline from April to December 2023, followed by a slight increase in February 2024. It ranged from 2.26 (December) to 3.57 bits/ind. (April), with lower values during the dry season (December and February) (Figure 8(A)). At the spatial scale, however, the values ranged between 3.06 (S5) and 3.45 (S1) bits/ind., with a decrease in diversity at the sampling stations (S4 and S5) located downstream of the leachate discharge into the stream (S3) (Figure 8(B)). Regarding the distribution of organisms in the environment, Pielou's index did not faithfully follow the same pattern as that of the Shannon and Weaver diversity index, both temporally and spatially. On the temporal level, values ranged from 0.6 in December to 0.75 in

October, the month during which the peak was observed (**Figure 8(A)**), while between stations, it fluctuated between 0.65 (S2) and 0.76 (S3), with a peak at S3 (**Figure 8(B)**). These results thus indicate a good distribution of organisms in the environment. The application of the one-tailed t-test on the Shannon and Weaver diversity indices and then on Pielou's index over the spatio-temporal scale shows that the values of these indices presented significant differences ($p < 0.01^{**}$) in both spatial and temporal aspects.

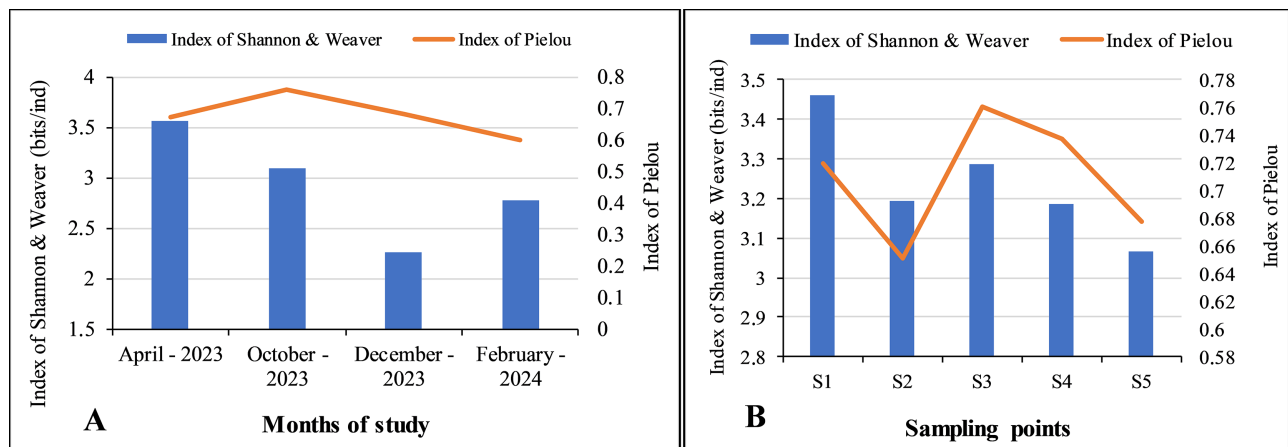


Figure 8. Temporal (A) and Spatial (B) variations of Shannon (H') and Pielou indices during the study period.

3.3. Environmental Drivers of Phytoplankton Structure and Diversity

The analysis of relationships between physicochemical parameters and phytoplankton structure revealed that nutrient-related variables and mineralization indicators were the main drivers of community patterns. Ammonium (NH_4^+), orthophosphates (PO_4^{3-}), and electrical conductivity showed the strongest positive associations with dominant taxa, particularly diatoms (e.g., *Bacillariaceae* and *Naviculaceae*) and some cyanobacteria, which were more abundant at impacted stations (S3, S4 et S5). Conversely, these variables were negatively associated with taxonomic richness and the Shannon diversity index (H'), indicating a reduction in community complexity under nutrient-enriched conditions. Dissolved oxygen exhibited a positive relationship with species richness and diversity, especially at upstream stations, while temperature and pH showed moderate associations, mainly influencing seasonal variability rather than overall community structure. These patterns suggest that nutrient enrichment and ionic content are the primary environmental gradients structuring phytoplankton assemblages in the study area.

4. Discussion

4.1. Physico-Chemical Variables

The water of the Ntinchoueh stream showed an average temperature of $21.3^\circ\text{C} \pm 0.24^\circ\text{C}$ during the study, relatively low compared to that obtained by Nsangou Moundignigni *et al.* in the Central Region ($23.2^\circ\text{C} \pm 0.02^\circ\text{C}$). This average tem-

perature, characteristic of the study area's temperature, rather reflects the evolution of water temperature in relation to ambient temperature [23]. Bouzidi *et al.* indicate that the environment and ambient temperature influence the temperature of surface waters [24]. The average pH of the water is slightly basic and falls within the range of values (6.4 - 8.36) obtained by Ngameni Tchamadeu *et al.* in the same study region [25]. This basicity would be due to the basic nature of the soils it flows through. The work of Zébazé Togouet indeed shows that the pH of a watercourse depends on the nature of the landscape it passes through [26]. However, the decrease in pH (7.11) observed at station S3, which receives leachate directly, would be caused by humic acid originating from the decomposition of organic waste from the landfill, which contributes to lowering the pH [27]. The high electrical conductivity values recorded at station S3 during the rainy season (1248 $\mu\text{S}/\text{cm}$) indicate the presence of significant water pollution caused by the introduction of leachate. Overall, the electrical conductivity values obtained in this study are much higher than the average of $56.22 \pm 4.31 \mu\text{S}/\text{cm}$ reported by Mbassi *et al.* [28]. These values are very low compared to those obtained by Foto Menbohan *et al.* where they recorded values sometimes exceeding 5000 $\mu\text{S}/\text{cm}$. According to the latter, the increase in mineralization results from the enrichment of streams by anthropogenic organic matter [29].

The average dissolved CO_2 content of $14.55 \pm 6.35 \text{ mg}/\text{L}$ obtained at S3 is higher than the 10 mg/L recommended by APHA and would indicate significant pollution and high biological activity in the watercourse [30]. The high values at certain stations can be explained by the respiration of aerobic organisms, which decrease O_2 while increasing CO_2 [31].

As for the nutrients nitrogen and orthophosphates, the average ammoniacal nitrogen content ($0.8 \pm 0.32 \text{ mg}/\text{L}$) is high compared to the values recommended by SEQ-Eau [32]. The highest value of 2.16 mg/L recorded at station S3 in February during the dry season would indicate the entry of a very concentrated leachate rich in this nutrient. The average content ($0.88 \pm 0.22 \text{ mg}/\text{L}$) of orthophosphate ions is higher than the $0.18 \pm 0.38 \text{ mg}/\text{L}$ obtained by Nyamsi [33]. In this regard, Rodier *et al.* (2009) [17] states that orthophosphate levels above 0.5 mg/L are an indicator of pollution. The peak of 2.093 mg/L recorded in October at station S5, located downstream of the studied impact, would result from the accumulation of pollutants due to the reduction in slope and the diversification of pollution sources, notably the leaching of phosphate fertilizers from agricultural watersheds [34].

Overall, the values of the physicochemical parameters recorded during this study are lower than those obtained in a similar study on the influence of municipal discharges on the physicochemical and biological quality of urban aquatic ecosystems: the case of the Massili River (Burkina Faso, West Africa) conducted by Kaboré *et al.* [35]. During this study, the pH of the water in the studied river ranged between 8.1 and 8.53; the electrical conductivity between 217.33 and 1921.33 $\mu\text{S}/\text{cm}$; ammoniacal nitrogen between 3.14 and 58.92 mg/L ; and ortho-

phosphates between 10.47 and 20.17 mg/L. Compared to the results of these two studies, the present study would therefore reveal an even lower physicochemical impact of the leachate on the physicochemical quality of the waters.

The observed spatial patterns confirm a clear gradient of environmental disturbance driven by leachate inputs. The significant differentiation of station S3 highlights its role as a critical contamination point, consistent with findings from similar studies on landfill-impacted aquatic systems [6] [36]. Elevated conductivity and nutrient levels at this station indicate strong mineralization and organic pollution, typical of landfill leachates [37].

The gradual decrease in pollutant concentrations at downstream stations (S4 and S5) suggests the occurrence of natural self-purification processes such as dilution, sedimentation, and biological uptake. However, these processes appear insufficient to fully restore water quality, as significant differences persist compared to upstream conditions. Seasonal variations further emphasize the role of hydrological dynamics, with rainfall enhancing pollutant transport and dry periods intensifying concentration effects [38] [39].

The elevated nutrient and organic matter levels observed at S4 and S5 suggest that water quality deterioration in the downstream section of the Ntintchoueh stream cannot be attributed solely to landfill leachate inputs, but rather to combined anthropogenic pressures. The presence of farms, leachate, and lye at S4, and the additional influence of sand extraction activities at S5, likely contribute cumulatively to the increased concentrations of NH_4^+ , PO_4^{3-} , and oxydability recorded in these stations. Such mixed impacts are known to intensify nutrient loading and organic pollution through both diffuse agricultural runoff and localized industrial disturbances, leading to compounded stress on aquatic ecosystems [36]. Similar synergistic effects of multiple land-use pressures on freshwater quality have been widely reported in tropical river systems, where overlapping anthropogenic activities exacerbate eutrophication and organic enrichment processes [6].

4.2. Phytoplankton Biodiversity

The species richness of phytoplankton during this study amounted to 57 species. This species richness is lower than the 80 species found in the Nkam river, which is also subject to physical and chemical disturbances that lead to a progressive deterioration of water quality [40]. It is also significantly lower than the 135 species recorded in the Foulou river, which is influenced by leachate from the HY-SACAM landfill in Yaoundé [41]. The difference in species richness among the three studies could be explained by differences in eutrophication levels or by the flow velocity of the studied watercourses. Furthermore, the low level of human activity in the watersheds of the studied watercourse section would limit the input of nutrients necessary for phytoplankton development. Regarding the specific richness of the different phytoplankton Classes; Diatoms are always the dominant Class [40] [41]. This result can be explained by the fact that Diatoms constitute a particularly diverse and ubiquitous algal class [42]. Similarly, in terms of the den-

sity of the different Classes identified in this study, the Diatom Class also dominated the others. Indeed, Diatoms, in terms of abundance, multiply rapidly and tend to dominate phytoplankton communities [43].

According to the variation in species richness and the density of identified species, spatially, the low taxonomic diversity (20 species) and species densities observed in sampling points S3 and S4 are likely due to environmental changes caused by the arrival of leachate, which will only favor the development of pollution-resistant species. These results indicate a clear disturbance gradient linked to leachate inputs, with reduced diversity and dominance of tolerant taxa at impacted sites, consistent with phytoplankton responses to pollution [44] [45]. The partial recovery downstream suggests self-purification processes, though insufficient to restore initial conditions. Seasonal patterns highlight the influence of hydrological dynamics on phytoplankton structure [38] [39]. In polluted aquatic environments, space and nutrient resources are monopolised by a small group of species, which prevents the development of a greater diversity of phytoplanktonic organisms [46]. Despite their low representativeness in terms of diversity and density, this study noted an increase in Euglenophyceae at sampling points S4 and S5. This observation could be explained by the fact that Euglenophyceae are characteristic of environments rich in organic matter [47]. In terms of timing, however, the greatest diversity (39 species) recorded in April is thought to be linked to the purification of the environment by rainwater and its recolonisation by new species. This result reflects the multiplicity of adaptive strategies implemented by microalgae to respond to biotic and abiotic stresses [45].

Furthermore, the analysis of occurrence frequencies revealed that the majority of species (40 species, *i.e.*, 70.17%) were classified as accessory taxa, reflecting the disturbed nature of the studied watercourse. Similarly, the variability observed in species distribution highlights the strong influence of station-specific characteristics and seasonal fluctuations in physicochemical parameters on the presence or absence of phytoplankton taxa within the environment, in agreement with previous findings [48]. Regarding the Shannon and Weaver diversity indices obtained during the study, the average value of 3.23 ± 0.11 bits/ind. observed spatially indicates that the studied population is relatively diverse. The maximum value of 3.45 bits/ind. recorded at sampling point S1, chosen as a control, shows that it is less affected by pollution, in contrast to S3, S4, and S5. This result is close to the values obtained (4.09 to 4.54 bits) by Taffouo *et al.* [40] in the Nkam river, where the physico-chemical variables indicative of pollution were low. As for Pielou's evenness, the average values in the spatial (0.70 ± 0.03) and temporal (0.67 ± 0.04) dimensions, which are greater than 0.5, indicate that a maximum number of species contribute to covering the water surface [49].

4.3. Physico-Chemical Variables Influencing Phytoplankton Diversity

The observed relationships confirm that nutrient enrichment, particularly nitrogen and phosphorus inputs, plays a central role in shaping phytoplankton domi-

nance and diversity in aquatic ecosystems. High concentrations of NH_4^+ and PO_4^{3-} promote the proliferation of tolerant and opportunistic taxa, especially diatoms and cyanobacteria, often leading to reduced species richness due to competitive exclusion under eutrophic conditions [50]. This negative relationship between nutrient levels and diversity has been widely documented in tropical and subtropical systems, where excessive nutrient inputs contribute to community simplification [35]. Additionally, the strong influence of electrical conductivity highlights the role of dissolved ions in structuring phytoplankton communities along pollution gradients [2]. In contrast, higher dissolved oxygen levels are typically associated with better ecological conditions and support more diverse and balanced communities. Similar patterns have been reported in recent studies, emphasizing nutrients, conductivity, and temperature as key drivers of phytoplankton composition and diversity across freshwater ecosystems [50].

4.4. Study Limitations and Hydrological Constraints in Data Interpretation

A key limitation of this study is the absence of hydrological variables such as stream discharge and flow velocity, which constrains a more precise interpretation of pollutant dynamics along the Ntinetchoueh stream. Without flow data, it is difficult to accurately quantify dilution processes, contaminant transport, and the role of hydrodynamic conditions in shaping spatial patterns of water quality and phytoplankton distribution. This limitation also restricts the ability to fully assess the stream's self-purification capacity, which is strongly controlled by hydraulic residence time and discharge variability [38] [39]. Consequently, while spatial trends in physicochemical and biological parameters can be identified, the relative contribution of hydrological versus anthropogenic drivers remains partially uncertain, as highlighted in similar studies on impacted river systems [2].

5. Conclusion

This research, which aimed to study the impact of leachate from the Bafoussam municipal solid waste landfill on the physicochemical quality and phytoplankton community of the Ntinetchoueh stream, shows that the arrival of leachate modified certain physicochemical parameters. It increases CO_2 , electrical conductivity, oxidability, and orthophosphates, but rather decreases the pH and dissolved oxygen in the water of the studied stream. The study also identified 57 phytoplankton species distributed across 12 families, with a predominance of Diatoms. From S1 to S5, the diversity and densities of phytoplankton are distributed according to the temporal variation gradient of the studied physicochemical parameters. The lowest diversity and density were recorded at S3, which receives leachate directly. Additionally, the development of Euglenophyceae, which indicate organic pollution at S4 and S5, demonstrates the continued influence of leachate on the biological community up to more than 2 km from S3. The Shannon and Weaver diversity index values showing what the specific diversity of phytoplankton is in the Nti-

netchoueh stream. Pielou's evenness greater than 0.5 indicates a good distribution of individuals among species.

Author Contributions

Talla Ngangni Charly Idriss wrote the article, conducted the field work, Nsangou Moundignigni Hénock Yves and Ameli Kenne Carole assisted to collect the samples in the field and analyzed them in the laboratory. Zébazé Togouet Serge Hubert and Djocgoué Pierre François co-supervised the work and read the manuscript.

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Conflicts of Interest

No conflict of interest to report.

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