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Influence of local and global environmental parameters on the composition of cyanobacterial mats in a tropical lagoon (Ebrié Lagoon, Ivory Coast)

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Abstract
We evaluated phytoplankton abundance, composition and trophic state of the Ebrié Lagoon on the basis of data taken in the period of June 2006 to February 2007. Sampling was performed at 13 stations in lagoon. Among three identified Cyanobacteria orders, Oscillatoriales dominated the peuplement with 47.62%. The distribution of the Oscillatoriales orders shows a predominance of genera Oscillatoria mainly composed of *Oscillatoria* cf. *leonardii*, *Oscillatoria princeps* and *Oscillatoria limosa*. The Chroococcales and Nostoccales constitute about 28.57% and 23.81% respectively of the total taxa. The blooms of Cyanobacteria in the lagoon were contributed by seven species. Those are *Cylindrospermopsis raciborskii*, *Anabaena flos-aquae*, *A. planctonica*, *Anabaena* sp., *Oscillatoria limosa*, *Lyngbya martensiana* and *Microcystis aeruginosa*. Abundance and seasonality of Cyanobacteria observed, characterized the Ebrié Lagoon as a highly eutrophicated environment. The NO_3^-, SiRD and PRD, salinity regime and tranparency availability played important role in determining the distribution, diversity, and composition of Cyanobacteria communities.

Keywords: Ebrié lagoon; cyanobacteria; composition; diversity; eutrophication

1. Introduction
Coastal lagoons are highly dynamic environments that show large spatial and temporal variability in their physical and chemical characteristics in response to the influence of freshwater and marine water inputs [1]. Moreover, as a consequence of the high sediment surface area to water volume ratios in coastal lagoons, processes occurring within the sediments and at the water-sediment interface strongly influence the ecosystem metabolism, nutrient budgets, and biota [2]. These processes have been exacerbated by the pressures of human activities on coastal systems, which have dramatically increased in the last few decades and are predicted to continue growing, especially in developed countries [3, 4]. These environments conditions are hostile to most forms of life, disturbing the equilibrium of the environment, disfiguring the landscape and, above all, destroying natural habitats used by the many migratory bird species. However, they harbor significant populations of microorganisms. The colonization of biota by primary producers (Cyanobacteria) demonstrates that such organisms can adapt to extreme ecological niches [5]. Indeed, some species of Cyanobacteria have ability to incorporate nitrogen. *Cylindrospermopsis raciborskii* has the capacity to fix atmospheric nitrogen (N2) through heterocytes, as do other Nostocales, conferring a competitive advantage in nitrogen-depleted environments [6]. Due to their capacity for photosynthesis, Cyanobacteria can rapidly become dominant in aquatic and terrestrial habitats by forming intensive blooms. The development of cyanobacterial blooms has become a serious problem in recent decades, because many bloom-forming species are reported to be able to produce secondary metabolites toxic to many organisms, including humans [7]. These can have a strong negative effect on water quality, as certain species of Cyanobacteria are capable of producing toxins. Increased dominance of Cyanobacteria on coastal lagoon is a continuing phenomenon in near shore tropical environments, particularly in areas impacted by humans [8].
In the Ebrié Lagoon, the blooms of Cyanobacteria have been observed [9]; they usually are dominated by Oscillatoria and Microcystis generus. Freshwater habitats in Ebrié lagoon are relatively poorly known from a Cyanobacteria ecology perspective, although the phycological from this lagoon have been documented by Seu-Anoï *et al*. [9]. In Southern region of Ivory Coast, studies include Seu-Anoï *et al*. [10, 11, 12, 13, 14] who studied phytoplankton of Aby, Ebrié

and Grand-Lahou lagoons respectively. Of the entire aforementioned checklist, none specifically reported the Cyanobacteria ecology in Ebrié lagoon. To evaluate the influence of abiotic environmental factors on the phytoplankton succession and for comparison with eutrophic ecosystems from higher latitudes, we analyze the variations in the composition of the Cyanopro karyote community during an annual cycle. In particular, we focus on environmental parameters such as the salinity, nutrient concentrations and weather conditions, since these are major factors expected to influence phytoplankton succession and Cyanobacteria dominance.

2. Material and Methods

2.1. Description of Study Area

Ebrié lagoon system is located in the far south-east of the coast of Ivory Coast between 5°02'-5°42'N and 3°47'-5°29'W (Figure 1). The lagoon system consists in Potou Lagoon, Aghien Lagoon and the Ebrié Lagoon. The main characteristics of these lagoons and tributary rivers are shown in Seu-Anoï *et al*. [10] (Table 1). The Ebrié lagoon system is connected to the sea by an artificial channel (Vridi Channel) and is the largest lagoon in West Africa with a total area of 524 km^2 [15]. This lagoon system falls under the "restricted lagoon" class according to the Kjerfve [16] classification. It extends over 140 km of the coastline with a mean depth and a width of 4.8 m and 7 km, respectively [17]. The Ebrié lagoon system is surrounded by mangrove forests and the annual freshwater inputs from Comoé River, which is estimated to be ~7 km3 representing ~3 times the total volume of the lagoon system, while the flow of seawater is ~14 times this volume [18]. The lagoon system is strongly polluted by domestic and industrial waste water inputs [15]. The waters around Abidjan are highly eutrophicated, leading to frequent oxygen depletion, massive fish kills and repelling sulphuric smells [19], and have been included in the recent compilation of coastal "dead zones" [20]. It is important to highlight that the Ebrié lagoon system is a restricted lagoon system where marine influence is more important. The climate in the study area is close to equatorial, having two rainy seasons separated by two dry seasons [21]. The long rainy season (LRS) occurs from May to July and is followed by the short dry season (SDS) from August to September. The short rainy season (SRS) starts from October to November while the long dry season (LDS) occurs from December to April. The annual rainfall is about 2000 mm

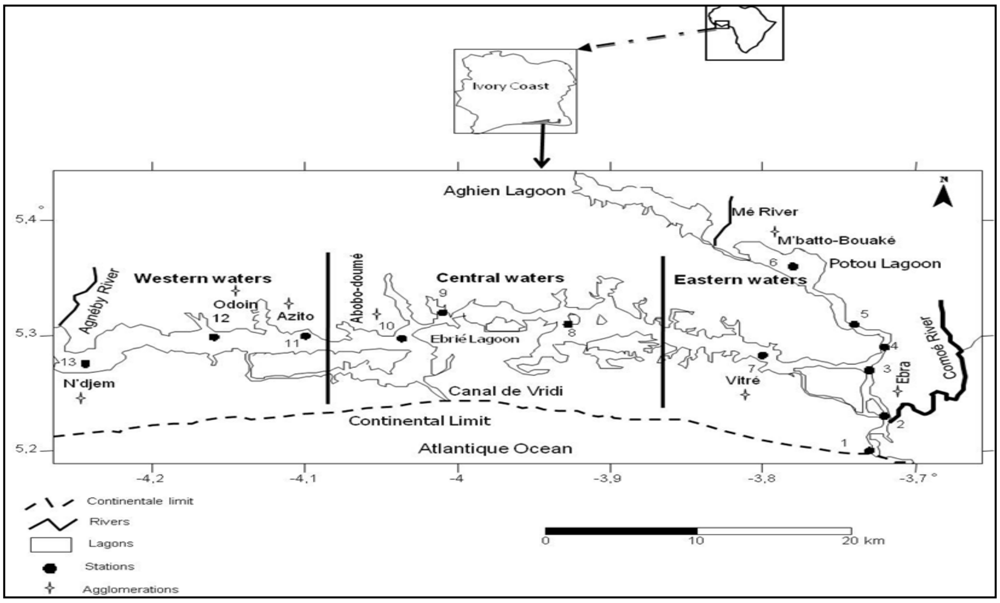


Fig 1: Location of the study stations in Ebrié Lagoon, Ivory Coast.

Table 1: Main morphometric characteristics of Ebrié system lagoon and of the main rivers (Mé, Comoé and Agnéby) flowing into this system lagoon (unpublished data from Koné *et al*. [19]).

Ebrié system lagoon	Area (km^2)	Volume (km^3)	Mean depth (m)	Rivers	Total length (km)	Drainage Area (km^2)	Mean water discharge (m^{3}s^{-1})
Aghien	22	-	-	Mé	140	4300	47
Potou	21	0.03	2.7				
Ebrié	523	2.6	4.8	Comoé	1160	78000	224
				Agnéby	200	8900	27

2.2. Sampling Site

Thirteen stations were collected in the whole lagoon system, except for Aghien Lagoon, during four seasons in 2006-2007 (Figure 1). Based on nutrient sources and salinity gradient, the 13 stations represented four main regions: eastern waters (1-7), which are under the influence of Mé River and Aghien Lagoon (stations 6, 5 and 4); and Comoé River (stations 1, 2, 3 and 7); central waters (8-10), which are close to Abidjan city and dominated by high anthropogenic pressure, high salinity coastal/shelf seawater; western waters (11-13), which are influence of Agnéby River.

2.3. Collection of Sample

2.3.1. Physical and Chemical Analysis of Water

Temperature, disolved oxygen, salinity and pH were determined *in situ* using a WTW COND 340-i conductivity meter for temperature and salinity, and an ORION 230-A meter for pH. Two standard buffer solutions (NBS4 and

NBS7) were used for pH meter calibration each day before sampling [22]. Water transparency was measured using a Secchi disc. Water samples for nutrient measurements were filtered through Sartorius cellulose acetate filters, refiltered through 0.2 µm pore size polysulfone filters, and preserved with HgCl2 for NO_3^- and soluble reactive phosphate (SRP), and with HCl for soluble reactive Si (SRSi). Concentrations of NO_3^- were measured on a Technicon Auto Analyser II [23], with an estimated accuracy of ±0.1 µmol L^{-1} and a minimum detection limit of 0.05 µmol L^{-1}. SRP and SRSi concentrations were obtained by using standard colorimetric methods [24], with an estimated accuracy of ±0.01 µmol L^{-1} and ±0.1 µmol L^{-1}, respectively. Minimum detection limits for SRP and SRSi were both 0.1 µmol L^{-1}.

2.2.2. Cyanobacteria Sampling and Analysis of Biotic Variables

Thirteen stations were collected in the whole lagoon system, except for Aghien Lagoon, during four seasons. The samples were collected during the period from June, September and November 2006 and in February 2007 using phytoplankton nets (20 µm mesh) in pelagic zones. The location of the 13 sampling stations was reported on the map of southern Ivory Coast (Figure 1). The net was dragged horizontally for 6 m in the surface water to obtain a sample of Cyanobacteria. Samples fixed in formalin solution (5% final concentration) were collected from a dyke or from the shore. For species identification, Cyanobacteria samples were examined in the laboratory using an Olympus BX40 microscope equipped with a calibrated micrometer. The classification proposed by Compère [25] and Komárek and Anagnostidis [26] was adopted for systematic taxonomic arrangements above the family level, and Komárek and Anagnostidis [26] for family and lower taxonomic levels. The quantitative estimation of the Cyanobacteria was performed by counting with an inverted Diavert microscope, using the Utermöhl [27] technique. Subsamples (25 ml) were settled in cylindrical chambers and left to sediment for at least 16 h. Cyanobacteria community counts were made under phase contrast illumination at 400–1000× magnification. The counts of unicellular, colonial, or filamentous algae were expressed as cells L^{-1}. Tow indices were used to obtain the estimate of species diversity. The Shannon and Weaver [28] diversity index (H) and Pielou's [29] evenness index (J) was calculated.

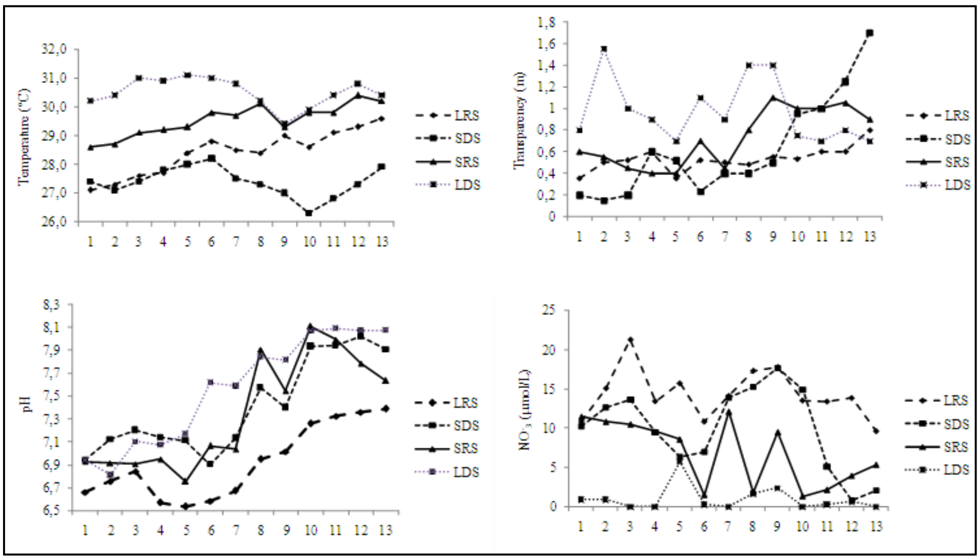
2.4. Statistical Analyses

To explore the principal patterns of the phytoplankton distribution and their relation with the environmental variables, we selected redundancy analysis (RDA) using CANOCO software [30]. Abundance data equal to or above 10% of the total numbers were taken into account (Table 2). Abundance values were log ([100 × abundance] + 1) transformed to prior analysis [30]. Pearson correlation analysis was used to test the significance of relationships between biological and physicochemical parameters. The analysis was based on pH, soluble reactive phosphorus (SRP), nitrate (NO_3^-), salinity, transparency, temperature and dissolved silicate (SRSi).

3. Results

3.1. Water Chemistry

Spatial and temporal variations of physical and chemical parameters of water in the Ebrié Lagoon surveyed are showed in Seu-Anoï *et al.* [11]. The temperature at the water surface varied across seasons in all stations (Figure 2A). During the survey, the temperature fluctuated between 26.3 and 31.1 °C. The higher values were obtained during the long dry season in all stations. Generally, the short dry season was characterized by lower temperature values. A clear temporal and spatial variation in pH and salinities was observed in all seasons (Figures 2B, C). Those parameters were higher during the long dry season (LDS) and lower during the rainy season at all sites. The pH oscillated between 6.54 to 8.11 (Figure 2B). The salinities values fluctuated between 0 and 27.5. Transparency was lowest (close to 0.15) in all stations during the long dry season (LDS) and high (up to 1.7) in sector II during the short dry season (SDS) (Figure 2D). Nitrate (NO_3^-) concentration exhibited a clear seasonal variation in all stations, with the lowest (0 µmol L-1) during the long dry season (LDS) and the highest (21.56 µmol L^{-1}) during the long rainy season (LRS) (Figure 2E). Soluble reactive phosphate (SRP) concentration (showed no clear spatial or temporal pattern. However, soluble reactive phosphate concentration was low (0.04- 0.2 µmol L^{-1}) in regions I and II during the long dry season (Figure 2F). Generally, the soluble reactive silicate (SRSi) concentration was higher during the long rainy season in all regions (Figure 2G), while the lowest values were recorded in region IV during the short rainy season. The concentrations ranged between 20.72 and 143.31 µmol $L^{-1.}$



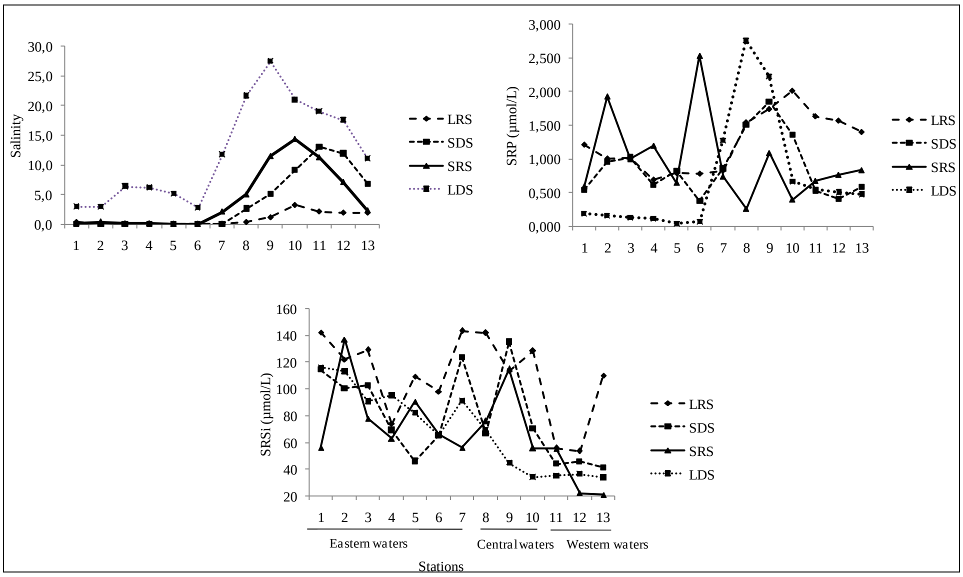


Fig 2: Seasonal and spatial variation in abiotic parameters at the study area (LRS: Long Rainy Season, SDS: Short Dry Season, SRS: Short Rainy Season, LDS: Long Dry Season)

3.2. Cyanobacteria Analysis

The Cyanobacteria of Ebrié Lagoon was composed of 21 taxa classified into 3 orders, 7 families and 14 genera. About 47.62% of the total Cyanobacteria taxa belong to the orders Oscillatoriales. The Chroococcales and Nostoccales constitute about 28.57% and 23.81% respectively of the total taxa. The distribution of the Oscillatoriales orders shows a predominance of genera oscillatoria mainly composed of *Oscillatoria* cf. *leonardii*, *Oscillatoria princeps* and *Oscillatoria limosa*. The Chroococcales were ably represented by the genera Merismopedia (constituted of *Merismopedia elegans* and *Merismopedia glauca*) and Nostoccales by the genera Anabaena (*Anabaena flos-aquae*, *Anabaena planctonica, Anabaena* sp.). The number of cyanobacterial species observed within the Ebrié lagoon system was unequal between the different stations. The highest diversity was observed in the eastern (at stations 1 and 4) and central waters (at station 8); the lower diversity was noted in the wasters waters (at station 11). *Nostoc caeruleum* var. *planctonicum* was present in half of the samples regardless of the nature of the area. The dominant species with relative abundance >2% of Cyanobacteria taxa for the 13 sampling sites are shown in Table 2. *Cylindrospermopsis raciborskii, Oscillatoria limosa* and *Lyngbya martensiana* were dominant species in samples from the stations 4 (eastern waters). The highest diversity was observed in samples from the eastern waters (stations 2) comprised more than 70% of the recorded species. However, the lower diversity was found, in generally, at western waters (at station 11, 13) with less than 40% of the recorded species (Figure 3).

The maximum Cyanobacteria abundance (708 10^6 Cells L^{-1}) was found during the long dry season at station 4 (Figure 4). The minimum (0.01 10^6 Cells L^{-1}) abundance was recorded, in generally, at all seasons in western waters (stations 11, 12 and 13).

Table 2: Cyanobacteria taxa that represented > 2 % of total abundance during the study period at stations

		Stations												
Taxons	**Acronymes**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Cyanoprocaryota														
Cyanobacteria														
Chroococcales														
Merismopedia elegans A.Braun	Meel	2,42	4,04	0	1,2	0	0	0	1,75	0	0	0	0	0
Merismopedia glauca (Ehrenberg) Kützing	Megl													
Microcystis aeruginosa (Kützing) Kützing	Miae	0	7,57	1,97	5,26	7,2	2,95	1,54	2,3	0	3,5	0	4	3,16
Oscillatoriales														
Lyngbya martensiana Meneghini	Lyma	1,5	0	0	10,53	2,3	0	4	1,02	8	0	2,22	3	3,16
Oscillatoria limosa C. Agardh ex Gomont	Oslm	1,5	3	9,4	21,05	9,52	4	4	1,2	1,6	0	0	1,4	0
Oscillatoria princeps Vaucher ex Gomont	Ospr	0	0	0	0	0	0	0	0	2	0	0	0	5
Cylindrospermopsis raciborskii (Wołoszyńsk) Seenaya & Subbar	Cyra	1,5	7,2	0	63,15	8,71	5,2	3	5	8,3	1,05	1,56	6,4	3
Leptolyngbya gracillima (Zopf ex Hansgirg) Anagnostidis & Komárek	Legr	5	0	3,42	8	8,1	6,45	3,52	4,08	4,6	8	5	8	1,43
Planktothrix agardhii (Gomont) Anagnostidis & Komárek	Plag	0	6,57	1,75	4,26	6,2	1,95	1,45	1,3	0	2,5	0	3	2,61
Nostocales														
Anabaena planctonica Brunnthaler	Anpl	1	0	0	8,25	2,1	0	3	1,25	7	0	1,22	2	2,10
Anabaena flos-aquae Brébisson ex Bornet & Flahault	Anfl	1,8	2	8,4	10,05	7,52	2	2.5	1,5	1,9	0	0	1,5	0
Anabaena sp.	Ansp	1,84	0	10	6	0	4	0	4	2	3	0	0	0

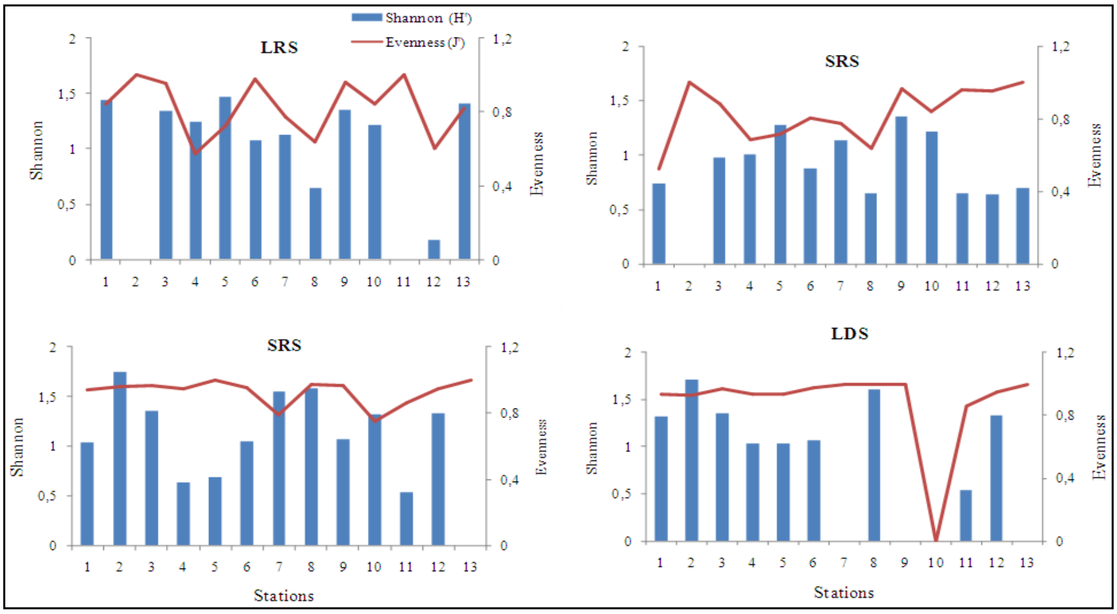


Fig 3: Seasonal and spatial variation in diversity (H') and evenness (J') of phytoplankton at the study area (LRS: Long Rainy Season, SDS: Short Dry Season, SRS: Short Rainy, LDS: Long Dry Season).

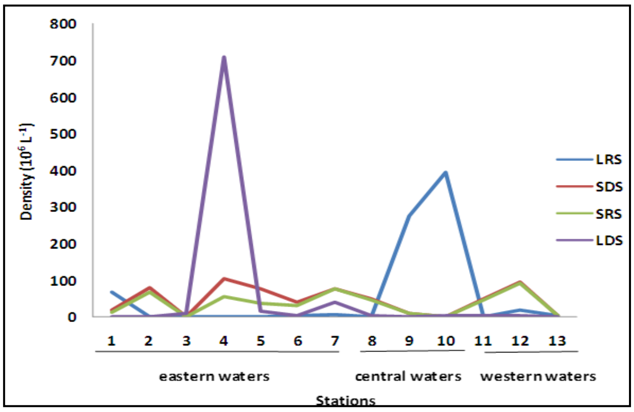


Fig 4: Seasonal and spatial variation in abundance of Cyanobacteria in the Ebrié Lagoon (LRS: Long Rainy Season, SDS: Short Dry Season, SRS: Short Rainy Season, LDS: Long Dry Season).

3.3. Correlation with Environmental Parameters

Redundancy analysis (RDA) on the 9 most abundant Taxa (Table 2) and 7 physical and chemical parameters (Figure 2) performed on the set of 52 samples showed the existence of correlations between the pattern of succession and the environmental parameters (Figure 5). The first and second axes of the Redundancy analysis (RDA) performed with species and environmental parameters explained 36.1% and 16.8%, respectively, of the total variance of the species matrix. The first axis, principally defined by the nitrates and temperature, presented the strongest correlation between species and environmental variables. The second axis was defined by the nutrients SRP, transparency and salinity (Figure 5). Two groups of samples and taxa can be distinguished in the graph: (I) samples from the long dry season (LRS), short rainy season (SRS) and short dry season (SDS); mainly characterized by mud in which *Merismopedia elegans* A.Braun ex Kützing (Meel), *Merismopedia glauca* (Ehrenberg) Kützing (Megl) *Microcystis aeruginosa* Meneghini, *Anabaena planctonica* and *Lyngbya martensiana* Meneghini Brunnthaler were the dominant taxa. These species were associated with the period of higher nitrates and PRD concentrations; (II) samples from long dry season (LDS) were dominated by taxa such as *Cylindrospermopsis raciborskii*, *Anabaena flos-aquae* Brébisson ex Bornet & Flahault, *Anabaena* sp., *Oscillatoria limosa* C.Agardh ex Gomont, *Leptolyngbya gracillima* (Zopf ex Hansgirg) Anagnostidis & Komárek and *Planktothrix agardhii* (Gomont) Anagnostidis & Komárek

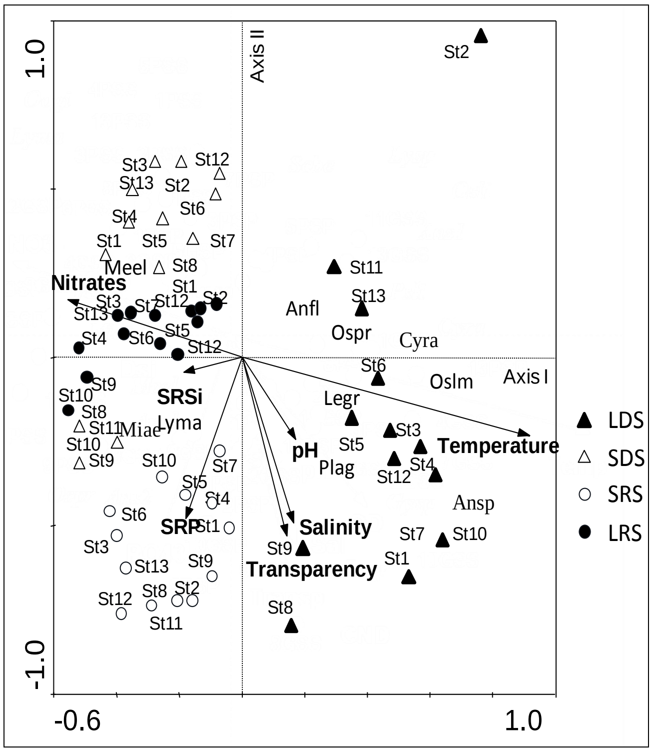


Fig 5: Triplots obtained through the RDA of physico-chemical variables, stations and Cyanobacteria abundance in Ebrié lagoon system (see Table 2 for abbreviations)

4. Discussion

The water temperature variation during the study period is in accordance with the values reported by Oneyma [31] for Lagos Lagoon, Kaźmierczak *et al.* [32] for the Nivå Bay, Seu-Anoï *et al.* [13] for the Aby Lagoon. The salinity and pH range, which varied seasonally, was highest during the dry season. According to Asmah [33], this reflects the seasonal change in insolation, which results in greater evaporation and hence in a higher concentration of salts in the dry months. During the rainy season, the high freshwater input from rainfall and/or water discharges inundates the entire lagoon, inducing a marked salinity gradient [34]. The pH values recorded during the study were alkaline in the dry months. Alkaline pH values recorded for the Ebrié system lagoon were an indication of high amount of CO_2 stored as forms of Carbonates in seawater producing a buffering effect [31]. A similar inference was reported by Kaźmierczak *et al*. [32] for the Nivå Bay, Onyema *et al*. [35] for the Lagos lagoon and Iyagbe lagoon, Asmah [33] for the Sakumo Lagoon (Ghana). In contrast, the lowest value of transparency observed during the long dry season (LDS) in the Ebrié system lagoon was due to the proliferation of the Cyanobacteria. Concerning the variability of nutrients, the concentrations were relatively high in the lagoon during the long rainy season (LRS). Nutrient enrichment in lagoons, such as that observed in the Ebrié system lagoon, has been found to be strongly related to polluted freshwater input from feeder streams, changes in water flow [36]. A similar observation was reported by Yankey *et al*. [37] in Tarkwa lagoon (Ghana). During the investigation period, the eutrophic character of Ebrié Lagoon was confirmed and the main representatives of its Cyanobacteria were identified; specifically, Oscillatoriales predominated in almost all of the samplings. The intense proliferation of Oscillatoriales in coastal eutrophic ecosystems is well documented in several studies [38, 39]. A similar situation, with a persistent dominance of Oscillatoriales, was described for the hypereutrophic Cabras Lagoon in Italy [1]. The Cyanobacteria species recorded for the entire study was similar to those reported previously in Ebrié Lagoon, Ivory Coast [40, 41], in Aby Lagoon system, Ivory Coast [14], in Bizerte Lagoon, Tunisia [42] and in Qua Iboe Estuary mangrove swamp, Nigeria [43]. However, the Cyanobacteria communities found in Ebrié Lagoon were low compared to those recorded in Aby Lagoon, Ivory Coast [40, 41, 44], in Aby Lagoon system, Ivory Coast [14] and in Laguna de Rocha, Uruguay [45]. This might be attributed to the quantities of anthropogenic wastes [46]. Indeed, the Ebrié Lagoon system receives organic pollutants in these wastes, such as raw human from its surroundings. Moreover, the number of phytoplankton taxa observed (21 specific and subspecific taxa) was not exhaustive because taxa under 20 µm were not collected in the plankton net.

In general, the Cyanobacteria is mostly represented by freshwater species, due to the fact that Ebrié Lagoon is strongly influenced by rivers such as Comoé, Mé and Agnéby, which allowed it to contain diverse organisms from freshwater. Moreover, most of the dominant taxa (*Microcystis aeruginosa*, *Aphanizomenon flosaquae*, *Phormidium* sp., *Cylindrospermopsis raciborskii*, *Oscillatoria tenuis*, *O. limosa*, and *Lyngbya martensiana*) were indicative of eutrophic conditions.

In the Ebrié Lagoon, Cyanobacteria experienced seasonal variation in their growth rates, leading to changes in their abundance. The low Cyanobacteria abundances observed during the long rainy season were more likely related to dilution processes rather than nutrient inputs from the rivers [47]. In addition, the brown water of the rivers in the long rainy season enriched the lagoon water in organic matter and thus reduced the transparency [48]. This most likely decreased the algal growth rates during this season. Indeed, during the long rainy season, the freshwater inflow in Ebrié Lagoon is too strong to allow biomass to build up, causing everything to be flushed out to sea. According to Bonilla *et al*. [49], freshwater discharged during this season into coastal environment can wash out phytoplankton biomass, preventing the development of blooms.

Ebrié Lagoon was characterized by proliferation of the taxa N2-fixing filamentous and filamentous non-heterocystous Cyanobacteria (gas vesicles species specially) during the long dry season because these species are able to grow in low NO_3^- conditions and have the capacity to fix atmospheric nitrogen [51]. Abundance values (0.01 10^6 to 708 10^6 cells L^{-1}) of Cyanobacteria in the Ebrié Lagoon are close to those observed in the tropical and temperate lagoons that varied from 0.01 10^6 to 934 10^6 cells L^{-1} [13, 14, 51].

The redundancy analysis indicated that the phytoplankton species distribution was significantly correlated with nitrates, SiRD and PRD during the rainy season (LRS, SRS) and dry short season (SDS) and with temperature, salinity and transparency during the long dry season (LDS). In fact, samples from the LRS, SRS and SDS were characterized by high abundance of taxa such as *Lyngbya martensiana* (Lyma), *Oocystis gigas* (Oogi), *Microcystis aeruginosa* (Miae), *Merismopedia elegans* (Meel) and *Anabaena planctonica* (Anpl). Samples from LDS were dominated by taxa such as *Cylindrospermopsis raciborskii* (Cyra), *Komvophoron minutum* (Komi), *Anabaena* sp. (Ansp), *Oscillatoria limosa* (Osli) and *Planktothrix agardhii* (Plag). According to George *et al*. [51] and Nassar *et al*. [52], the distribution of Cyanobacteria taxa is influenced by changes in the physical and chemical properties of the water which can be dependent on rainfall. Similarly, salinity is known to regulate the occurrence and distribution of biota in the lagoon.

5. Conclusion

The relation patterns described here represent the first observation of Cyanobacteria dynamics along the Ebrié system lagoon. This result provides new insight into the distribution of Cyanobacteria organisms along strong salinity gradients and allows for a better understanding of the overall pelagic functioning in saline systems which is critical for the management of these precious and climatically-stress ecosystems.

The study of the relationships between physicochemical and phytoplankton processes should be pursued in situations of changing environmental characteristics with pollution (discharges of domestic and industrial wastewater, and traditional and industrial agriculture) which continues to grow. In addition, the intense proliferation of Cyanobacteria is in the long run nuisances incompatible with the socio-economic activities of lagoon environments (fishing, swimming) and could have adverse consequences on the health of fish in the environment and on the health of populations. This proliferation also induces unfavorable ecological conditions for aquatic biodiversity. Therefore, a restoration study is necessary to reduce the proliferation of these Cyanobacteria considered as indicators of a eutrophyc level, by acting on the mechanisms regulating their development that is to the nutritive resources, by carrying out a policy of reduction of the nutrients entering the lagoon system.

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